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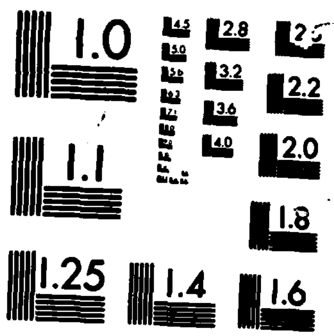

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An Investigation of the Use of Steady-State Evoked Potentials for Human Performance and Workload Assessment and Control

Final Report for Contract F49620-83-C-0102
June 1985

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Abstract

This program of research investigated Steady-State Evoked Potential (SSEP) measures to determine their utility for evaluating sensory inputs, workload, and performance variables in human operators. A primary purpose was to find techniques and measures that could be generalized to groups of subjects in operational environments. SSEP measures included power (amplitude), coherence, phase lag, and Relative Transmission Time (RTT).

Included in this effort were studies of :

1. Frequency "masking", where multiple frequencies were presented simultaneously.

2. Sensory inputs which may manipulate SSEP (eg. color, intensity, cross-modality stimulation).

3. Correlation of SSEP measures with fatigue and task difficulty.

4. The relationship between performance in a tracking task and SSEP measures.

The major findings are:

1. The RTT as determined in these studies had no sensitivity to any variable studied and is not a good candidate for future studies in its present form.

2. Auditory stimuli did not have an effect on SSEPs.

3. Coherence was the most sensitive measure of color and brightness variables. It suggested that it may be difficult to generate strong following with transmitted red colored whole field stimulation.

4. Phase lag and coherence showed differences in frequency of stimulation.

5. Coherence varied with workload in the Cross Coupled Instability (tracking) Task (CCIT).

6. Phase lag varied with frequency of stimulation and showed changes with fatigue and task difficulty as a function of frequency of stimulation.

7. The significant measures correlated with fatigue did not provide much additional information over conventional fatigue scales.

8. Coherence and phase lag are potentially useful measures of workload.

9. We observed drastic variation in individual subject SSEPs to various stimuli. For maximum effectiveness in SSEP research, it appears important to address individual differences and select each subject's most resonant frequencies for testing.

10. The brain's response to some frequencies, as measured by coherence, was suppressed in the presence of other stimulating frequencies for some subjects.

Introduction

The assessment of human workload has become an increasingly important topic for investigation as the design and efficient operation of modern systems becomes more complex and demanding. The need to integrate the human into these systems so that feedback and control is as automatic as possible has become critical. Methods of measurement and feedback, such as traditional behavioral measures, are often awkward to use, interfere with the operator's primary task, provide relatively slow feedback, and add to the operator's workload. Human electrophysiology measures, especially techniques utilizing evoked potentials (EP) offer the potential to avoid these difficulties.

The averaged evoked potential has been the most commonly used form of EP to investigate human perception and performance. While these potentials have been shown to correlate with a variety of internal and stimulus parameters, they usually must be elicited by a discrete event of some relevance to the operator. In operational environments, these stimuli are usually external and may interfere with the operator's primary function. In addition, some situations do not allow the opportunity to insert transient evoking stimuli at appropriate times. Other situations require constant monitoring with continuous evoking stimulation since the relevant time points are unknown prior to their occurrence.

Visual Steady-State Evoked Potentials (SSEP) are elicited by presenting a continuously flickering light stimulus to the observer. These EPs have been used to study visual system physiology (Regan, 1972), to detect the presence of demyelinating diseases (Milner, Regan, Heron, 1979), perform rapid objective refraction (Regan, 1973), and to examine human performance and workload (Moise, 1979; Wilson, 1980, 1981).

Recent investigations of human workload and performance using SSEPs strongly suggest that this tool measures certain cognitive and performance variables (Wilson, 1980, 1981). Moise (1979) investigated transient and steady-state EP measures to determine their suitability as metrics for assessing performance and workload. He concluded that the SSEP has considerable potential as a tool for assessment. Some of his studies demonstrated correlations between the SSEP, fatigue, and psychological factors.

When unpatterned stimuli are presented while flickering between 5 Hz and 60 Hz, three ranges of enhanced steady-state amplitudes (or "peaks") are found around 10 Hz, 18 Hz, and 50 Hz. Even though SSEP amplitude generally diminishes with increasing frequency of stimulation, the higher frequency range is of special interest since these stimuli are usually above the fusion point of flicker and are typically perceived as slightly

flickering, if at all. This provides the possibility of measuring SSEPs with minimal visual intrusion on a primary task.

There are two primary measures of the SSEP, amplitude and phase lag. Amplitude is a measure of the energy in the SSEP at the frequency of interest. Phase lag is the angular difference between sine wave components of the output of the brain and corresponding sine wave components of the stimulus input. From these measures can be derived the coherence, an intuitively appealing measure which is an indication of the degree to which the brain's output matches the input stimulus.

Another measure that may be computed is the Relative Transmission Time (RTT). This is a measure of the time for transmission of nerve impulses from eye to higher cortical centers (Regan, 1972). RTT has been useful for early clinical evaluation of visual pathway damage by demyelinating diseases. If the difference in RTT collected for each eye separately is greater than some threshold, demyelination or damage to one optic tract is indicated. Sometimes disease will attack one pathway before another and is therefore an early indicator. Since RTT is an estimate of the latency of transmission through the nervous system, it is of potential use in the study of workload.

To compute the RTT, at least three frequencies are presented to the visual system. If one assumes a constant lag time for all frequencies in a given range, it is possible to calculate the apparent latency of the SSEPs through the nervous system by calculating the slope of the best fitting straight line and dividing it by 360 degrees (Regan, 1972). The result may be thought of as a "relative" measure of transmission time since it is not possible at this time to know all the interactions between eye and electrode that contribute to this measure. It is clear, however, that this is not a simple indicator of neuronal transmission from eye to brain.

A rapid method for collecting data is to mix the stimulating frequencies together and present the resulting complex waveform to the subject (Regan, 1976). The brain responds to each of the stimulation frequencies, permitting the simultaneous collection of the require data.

Wilson (1980) has shown that the phase lag between stimulus input and the SSEP waveform was significantly related to task difficulty in a single axis tracking task. This correlation was observed for high frequency (50 - 56 Hz) but not medium frequency (14 Hz) stimuli. More recently, Wilson (1981) has reported a correlation between difficulty in a memory scanning task and the slope and intercepts (RTT) of three frequencies of flicker. Performance in a more difficult memory rotation task did not correlate with these EP measures.

The SSEP measures defined above are appealing and have strong face validity for measuring human performance factors. Dr Wilson

(personal communication) has begun an intensive program to investigate traditional stimulus parameter effects (intensity, flicker rate, etc.) on RTT.

Purpose of this Research

This document describes the accomplishments of a two-year program of research that investigated the utility of high frequency SSEPs as measures of workload, performance, and stimulus properties. Stimulation in this region was expected to minimize disruption in subjects engaged in operational tasks.

This program of research investigated:

1. Sensory inputs which manipulate SSEP (eg. color, intensity, cross-modality stimulation).

2. Correlation of SSEP measures with factors known to affect workload and performance, such as fatigue and task difficulty.

3. The relationship of performance variables (eg. tracking) to SSEP measures.

It is clear that SSEP measures show a considerable range of individual differences, especially in the high frequency range. Regan (1972) has reported individual subject differences in the frequencies which produced the maximum amplitude SSEP response. The absolute amplitude of these potentials is small and Wilson (1980) felt it essential to determine the nature of the SSEP response from each of his subjects.

However, a primary purpose of this research was to find techniques and measures that could be generalized to groups of subjects in operational environments. Therefore we did not individually tune the stimulation frequencies for each subject, but took values from the range of those reported for Regan and Wilson's subjects.

This research was conducted in the laboratories of the Psychophysiology Function at Brooks AFB. Details of the extensive process we went through to set up a data collection facility suitable for these experiments were presented in the Annual Report (1984) for this contract.

General Methods

This section presents a general overview of the methods, subjects, and equipment used in this research. Details relevant to each experiment may be found in the description of each experiment.

Subjects

NTI put together an outstanding Human Use Committee to review our research protocols and insure the continued safety and well-being of the subjects used in these investigations. This committee approved our procedures and agreed that they did not put our subjects at risk in any way.

A total of fifteen subjects, ranging in age from 27 to 44 years old, have been recruited from contractors, associated personnel, and the staff of the Psychophysiology Function at Brooks AFB. These subjects underwent a photically driven EEG examination that was interpreted by a qualified neurologist. Some subjects suffered from mild astigmatism and nearsightedness, but all were able to easily identify the small symbol used as a fixation point during data collection in some experiments. All subjects have signed an informed consent form which was approved by the Human Use Committee and obtained in accordance with AFR 169-3.

Apparatus

A. Electrodes and Recording Sites

Evoked potentials were recorded using silver-chloride electrodes applied with EC2 electrode cream (Grass Instruments) after cleaning the scalp with Omni Prep.

Pilot studies were performed with monopolar electrode placements (occipital midline referred to a left or right mastoid ground), and bipolar recordings between either midline occipital (Oz) and midline parietal (Pz) or Oz and midline central (Cz) sites (ten-twenty electrode system) with a mastoid ground.

Spekreijse (1966) describes the behavior of low and medium frequency SSEPs as appearing not to have dipoles. High frequency (above 45 Hz) SSEPs act as if they do have dipoles. From the figures in Spekreijse's paper, one can infer that monopolar recordings may not show photic driving if the electrode is located at the center of such a dipole. In our pilot subjects, the most robust driving generally was with bipolar Oz-Pz recordings and all subsequent data was taken with bipolar recordings from Oz-Pz.

Electrode impedances were under 5K ohms before recording began, with typical readings of less than 3K ohms. Impedances were checked again after the recording session. Data were retained only if pre- and post-experiment impedances were less than 5K ohms.

B. Recording System and Analysis

All data were recorded with subjects and visual displays inside an Industrial Acoustics Corporation (IAC) sound- and electrically-shielded chamber that measured 6 ft. 11 in. X 7 ft. 4 in. X 6 ft. 6 in. high. Light level within the chamber was less than 1 fl, except for the experimental stimuli.

For all data collection , two signals were recorded: the electrical voltage output of a photo detector circuit and the EEG (Figure 1). EEG electrodes were directly connected to a Beckman Dynograph recorder model R711. The Beckman patient box was bypassed when it was discovered that it permitted cross-talk between channels as well as unexpected filtering of the signals. Amplification of the EEG was 20,000 to 1 with a 100Hz low pass filter and a 0.16 Hz high pass filter. No 60 Hz notch filter was used.

The output of the photo detector circuit was also directly connected to a Beckman amplifier with all filter settings identical with the EEG. Amplification was 5 to 1.

Output of the Beckman was sent to a Fourier Analyzer (Hewlett Packard Fourier Analyzer, model 5441B) which digitized the analog signals and analyzed the data for its frequency content. The raw data was visually monitored by a Tektronix oscilloscope, model TM515.

No amplification of the raw signal was performed by the Fourier Analyzer. A program in the Analyzer sampled both channels 256 times a second for 10 to 20 seconds and provided power spectra of each channel, and cross power, phase lag, transfer function, and coherence between channels. This information was forwarded to a DEC PDP 11/34A for storage and data reduction. After transfer of the data to a PDP 11/70, statistical processing was performed using the BMDP and SAS statistical packages.

C. Stimulus Generation

The steady-state visual stimulus was produced by a pair of flickering fluorescent light tubes. The orientation and exact dimensions of the light tube arrangement in the experimental apparatus differed with each experiment. For all experiments, the center to center distance between the tubes was 2.75 in. Cool white, 8 watt tubes manufactured by Silvania, model number F8T5/CW provided the light.

In order to drive the fluorescent tubes with simultaneous multiple frequencies, a drive and mixing circuit was required. Since the techniques for multiple frequency steady-state have been refined at Wright Patterson AFB, we acquired a circuit diagram and description of an apparatus they used for this

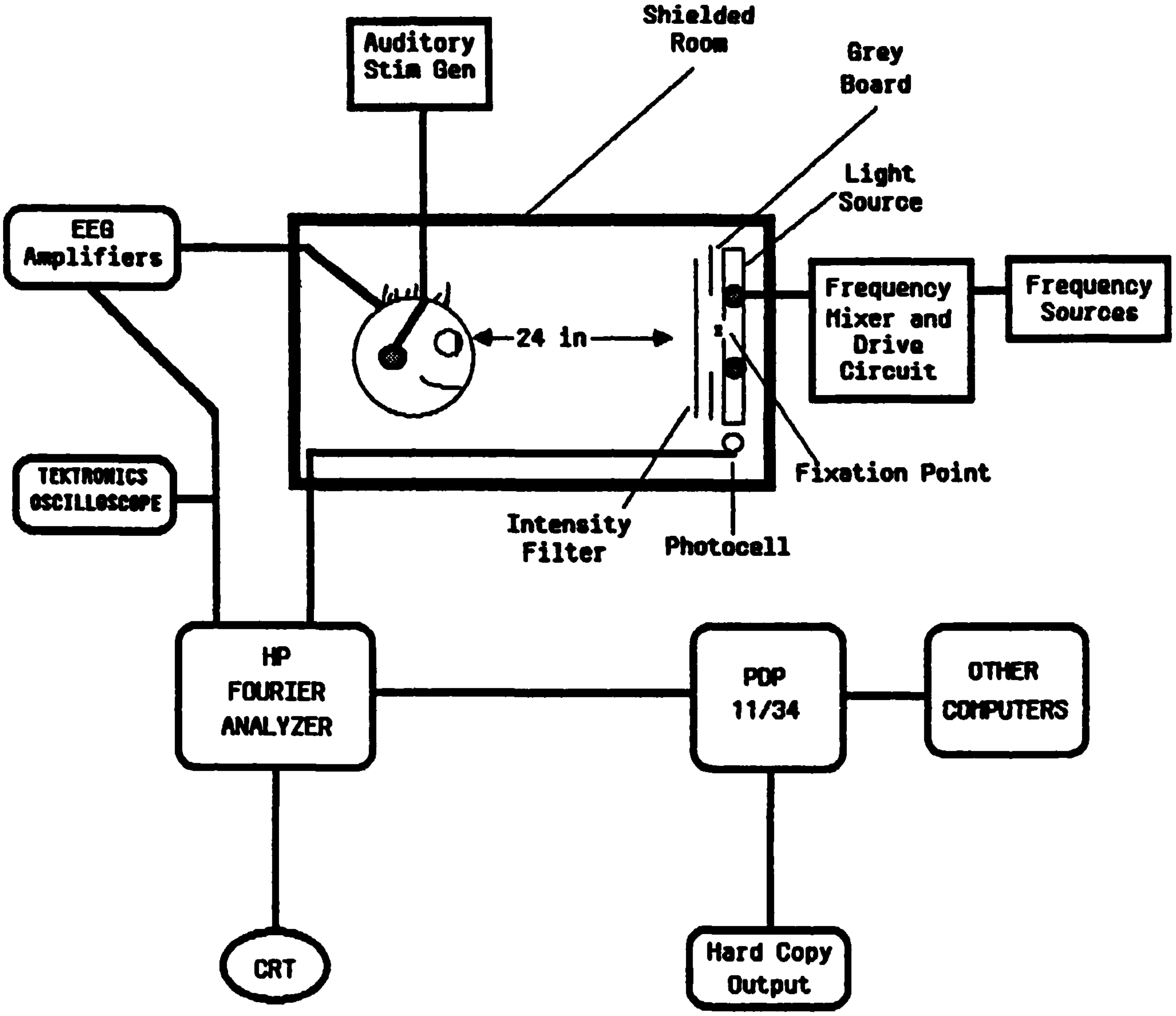


Figure 1. A schematic diagram of the subject and apparatus.
(Auditory Experiment)

purpose. The device purportedly allowed up to three frequencies to be mixed.

Unfortunately, the information provided was incomplete and a number of iterations were required before the circuit was functional. Eventually we were able to make efficiency improvements on the original in addition to getting it to work. A schematic of this circuit and a parts list may be found in the Appendix.

After the development of the multiple frequency circuit, we discovered that the design would only permit a maximum of 50 percent modulation depth. With three frequencies, this means a maximum of about 15 percent each. It is well known that modulation depth is an important variable in achieving clear steady-state driving and, for many subjects, 15 percent is inadequate. As we later found out, this is one of the reasons that this circuit is no longer used at WPAFB for experiments requiring more than two frequencies.

The three stimulating frequencies used in these experiments were 45, 48, and 51 Hz. A luminance of 150 ftl was measured for one degree of visual angle by a Minolta Luminescence meter. Light energy from the stimulus tubes was measured by a photo detecting circuit built from two Radio Shack photo detectors. The detector circuit was mounted 1.5 in. below the lower tube.

Pilot Studies

Pilot studies were run to refine the data collection system for control of equipment and power source artifacts. In addition, we examined the response of several subjects to our proposed multiple frequency scheme with various modulation depths and electrode placements.

We were concerned with the generally low coherences observed in some pilot subjects at the stimulating frequencies we used. We have determined that coherences greater than 0.20 are necessary to be confident that a subject is demonstrating a satisfactory level of photic driving. When three stimulation frequencies were simultaneously presented pilot subjects were frequently below the 0.20 coherence level with only an occasional subject above 0.50.

It is well known that modulation depth is a powerful influence on the brain's ability to follow a driving stimulus. Due to the limitations our equipment set on achievable modulation depth, we examined modulation depth effects on SSEPs in several subjects.

In his examination of SSEPs and tracking, Wilson used a modulation depth of 33%. Our pilot studies suggested that modulation depths of at least 20 per cent were necessary to produce reliable driving. This meant that we could not present a mixture of three frequencies as that would limit modulation depth

to only 15% for each. In order to systematically examine the effectiveness of simultaneously presented dual frequencies, we presented several subjects with pairs of frequencies modulated at 20-25 percent.

Stimuli were presented in pairs over the range 40 to 59 Hz. The starting pair was 40 and 50 Hz. Data was collected and each frequency was increased by 1 Hz so the next pair was 41 and 51 Hz. This continued until the last pair (49 and 59 Hz) was presented.

The surprising result for our first subject is shown in Figure 2 by the data points labeled Pairs. For each of the pairs, the higher frequency shows a dramatically lower coherence than the lower frequency! This is apparently due to the high frequency being paired with a lower frequency since unpaired single frequencies over the same range showed no such drop (the data points labeled Single in Figure 2). It is as if the lower frequency suppresses the coherence of the higher one in some sense. Each stimulus of each pair was intensity equated with each other and each single frequency to eliminate intensity as a variable. A second subject we ran also showed the same phenomena, but less strongly. Power (amplitude) of the SSEP did not change as a result of paired presentations in either subject.

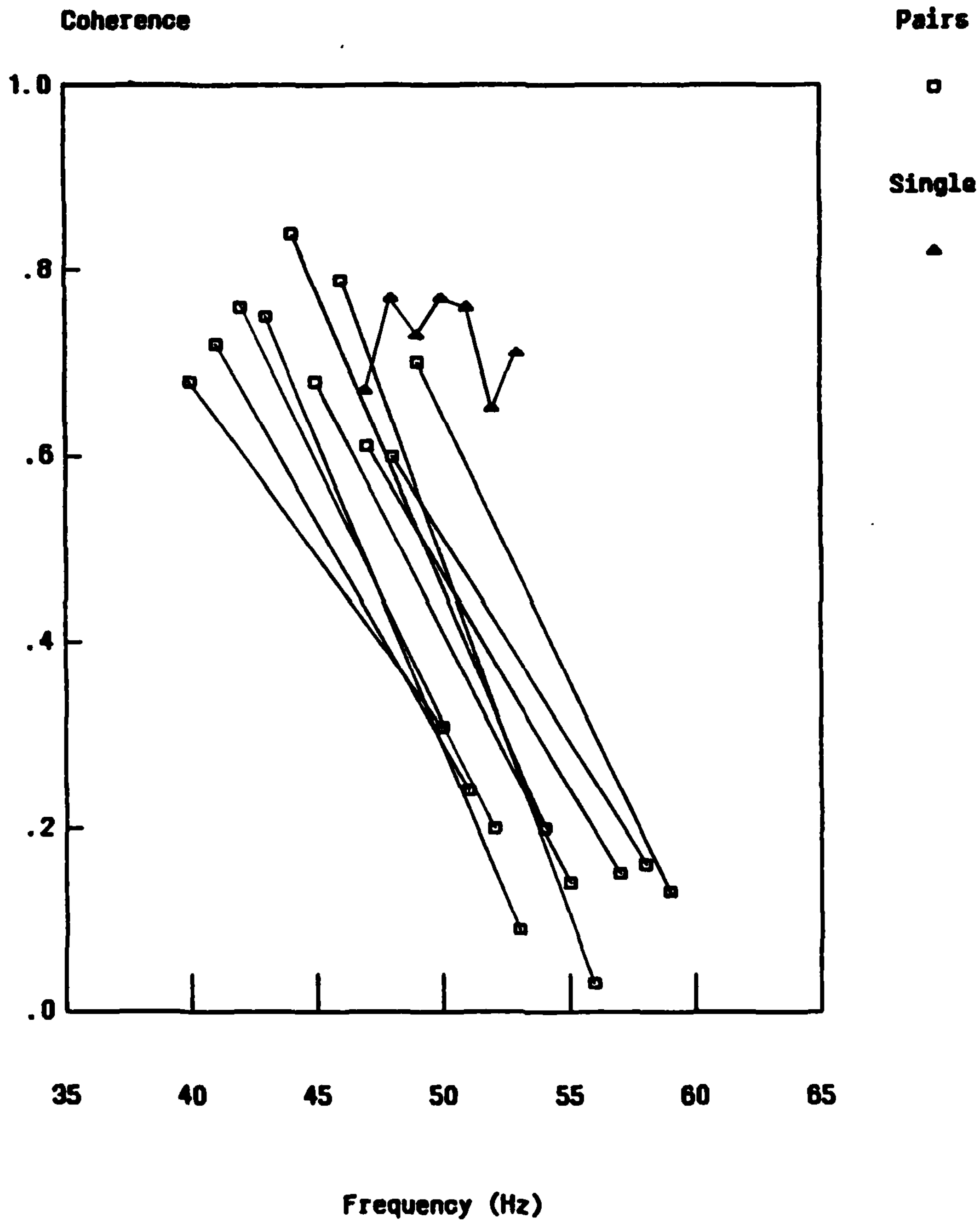
In order to determine if the behavior with pairs of stimuli was an equipment or computational artifact, we repeated the pairs experiment, but substituted a dummy EEG signal consisting of very small amplitude sine waves at the frequency of the stimulating light. In this case, all coherences were the same (.999) and we concluded that there was no equipment artifact.

If this were a repeatable phenomenon, it has intrinsic interest for understanding properties of the visual system. In addition, such a finding would have important implications for the findings of research conducted with simultaneously presented multiple frequencies. Researchers would have to account for possible contamination of their results due to suppression. To investigate these effects further, we ran additional subjects in a more formal study of the suppression effect.

Frequency Suppression Experiment

Six subjects were asked to observe a fixation point on a white sheet of paper 24 in. in front of them (similar to the arrangement in Figure 1). The steady-state visual stimulus was produced by the pair of fluorescent light tubes and drive circuitry described earlier. On the paper was presented either modulated mixed pairs of frequencies, or single frequencies over the same frequency range (Table 1). A randomized order was used to present three repetitions at each frequency. Intensity of each pair and each individual frequency was equated before

Figure 2. Coherence for paired and single frequencies for subject M.



presentation. Modulation depth for each frequency was 20% for each paired frequency as well as each singly presented frequency.

Table 1

Frequency Pairs	Singles
39-45	39
42-48	42
45-51	45
48-54	48
51-57	51
	54
	57

For all subjects as a group, there were no statistically significant differences in Power or Coherence measures as a function of frequency paring. However, there were two subjects who consistently showed the suppression effect for Coherence. The other four subjects showed a variety of relationships. Some subjects were run repeatedly for numerous trials over a period of several weeks. For these subjects, no matter what pattern they showed, they reliably reproduced those patterns over the entire testing period.

Paired data for the best subject (#81) is shown in Figure 3. It is clear that this subject consistently suppresses Coherence of the higher of a pair of frequencies as compared with the lower of the pair or with the level of singly presented frequencies.

Another way to view this data is to pick a center frequency and plot the effect of pairing with both lower and higher frequencies. Figure 4 shows such a plot for Subject 81 with 48 Hz as the center frequency. the center frequency appears suppressed when paired with a lower frequency, but appears almost as high as its singly presented level when paired with a higher frequency. Figure 5 shows a similar plot with 51 Hz as the center frequency.

This finding might be interpreted as a frequency analog to temporal masking phenomena found in visual and auditory perceptual and memory systems. Generally masking refers to the reduction or elimination of the recording or perception of a stimulus presented in close temporal proximity to another stimulus. In the present experiment, the stimuli were presented simultaneous in time, but separated in frequency.

The finding that subjects have unique responses to paired frequencies is not surprising given the reports of individual differences in responses to a variety of Evoked Potential parameters described earlier. Wilson and his associates have examined individual differences in the brain's response to a large number of high frequency (32-75 Hz) steady-state stimuli.

Figure 3. Coherence for paired and single frequencies for subject 81.

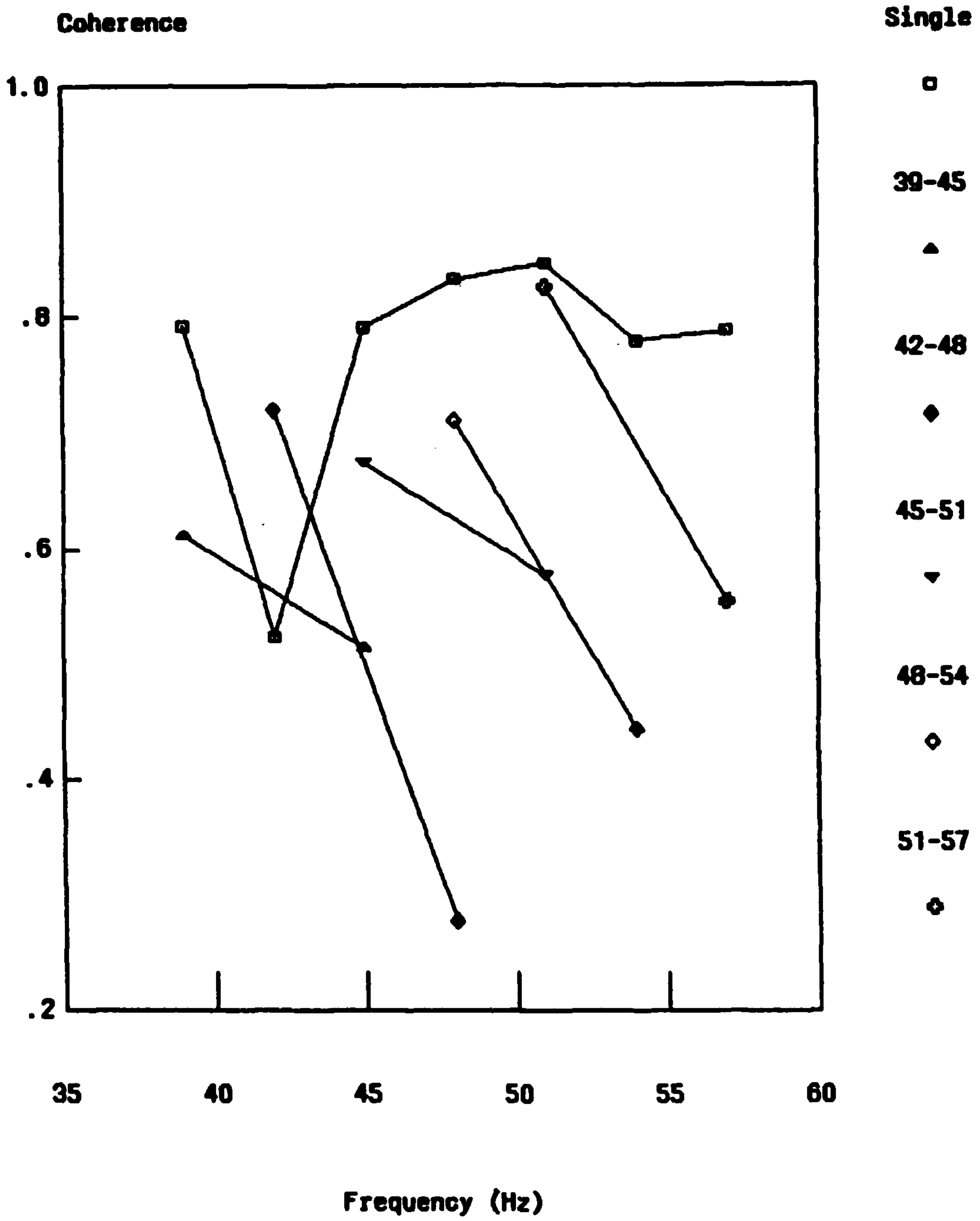


Figure 4. Coherence for frequencies paired with 48 Hz and single frequencies for subject 81.

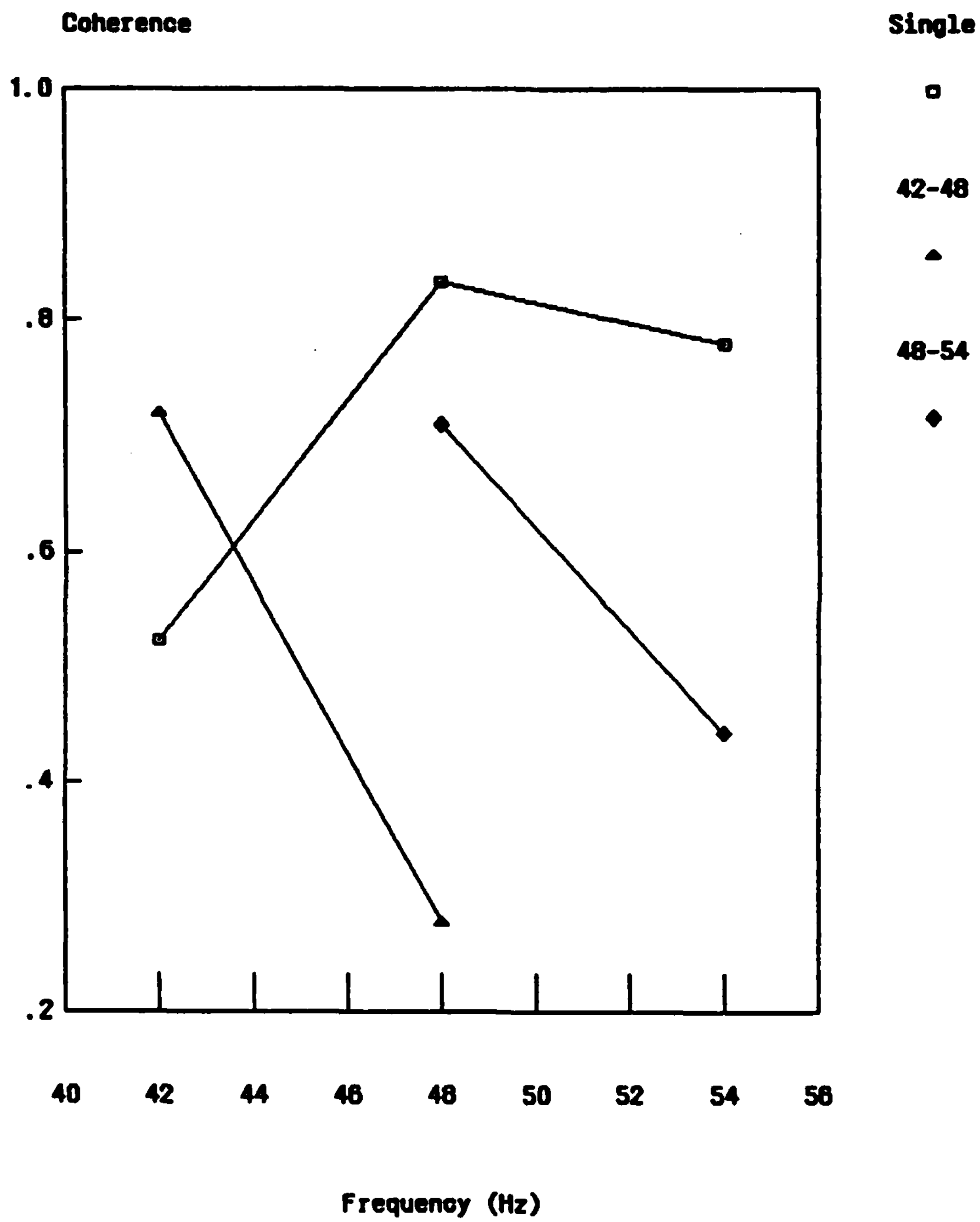
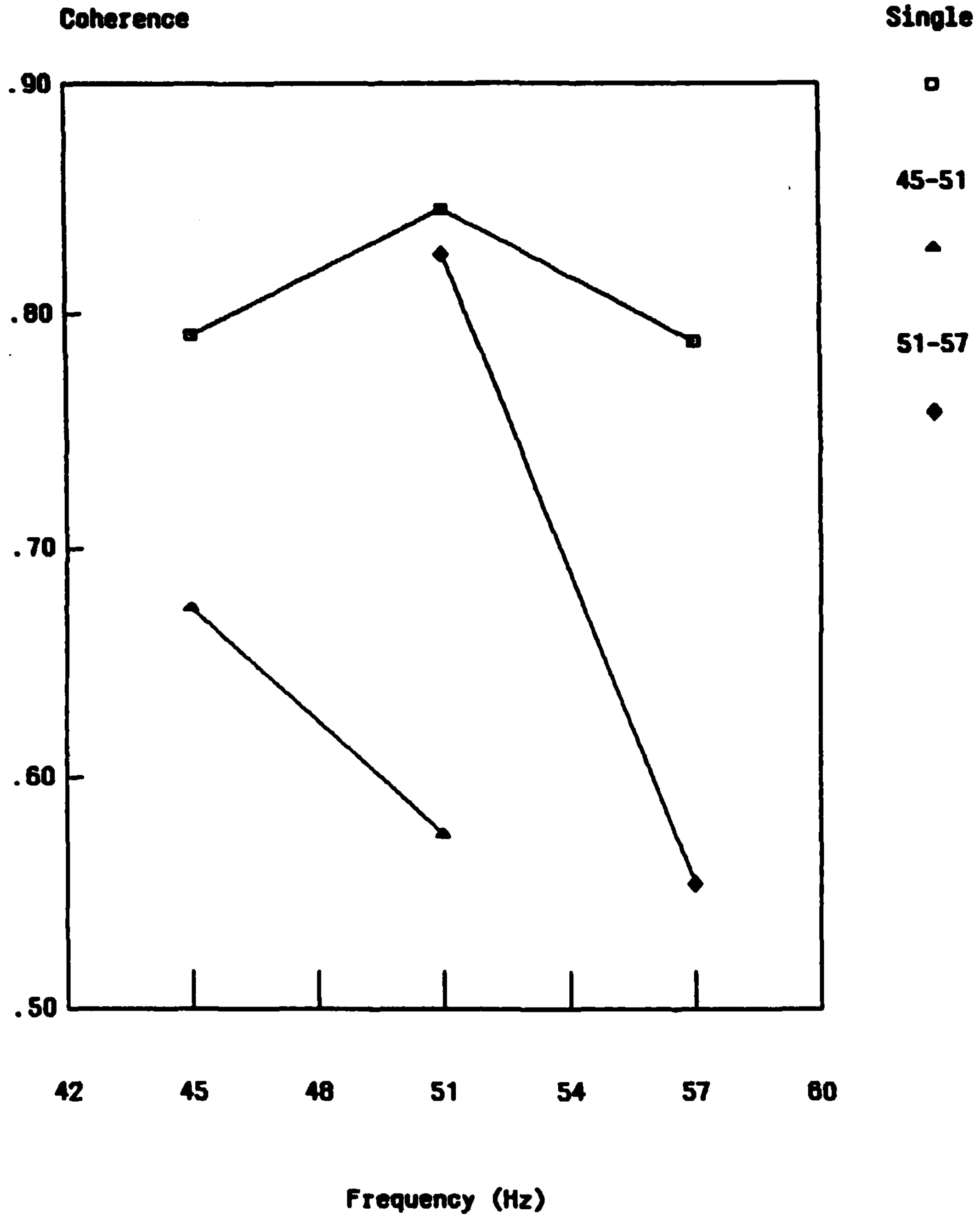


Figure 5. Coherence for frequencies paired with 51 Hz and single frequencies for subject 81.



They found considerable differences in individual's sensitivity to different frequencies. They have shown that each subject has his own sensitivity to various frequencies. They argue that best SSEP results are obtained only if the best frequencies for each subject are used.

The combined effect of having limited modulation depth with multiple frequencies, the variability associated with individual subject responses to different parts of the frequency spectrum and the possibility that in some Ss multiply presented frequencies may suppress the brain's response to each other, led us to collect all subsequent experimental data by presenting one frequency at a time. This method lengthens the time to collect data for the RTT measure and would seem to limit its prospective use in operational environments if these limitations persist.

While the simultaneous presentation of three frequencies permits rapid data collection for the RTT measure, there are advantages to the single frequency presentations. Virtually all subjects reported seeing beat frequencies when mixed multiple frequencies were presented. Some subjects reported that these beats were unpleasant and made fixation difficult. While this may be tolerable in the clinical setting, it would not seem desirable in the cockpit. Single frequencies in the range we are using appear flicker-free to nearly all subjects. Finally, single frequency presentation has been the most commonly used method by other researchers in this field.

In spite of clear evidence that individuals have unique sensitivities to steady-state stimuli, the purpose of this research was to determine if these measures have general applicability to groups of subjects. If such general attributes could be found, the problem of application in the real world would be considerably eased. Therefore the data analyses focus on group results, but individual data is shown where appropriate.

Auditory Stimulation Experiment

Very little research has been done concerning the effect of cross-modal stimulation on the SSEP. The usual assumption is that there is no effect of non-visual modalities on SSEP except as such stimulation may cause attentional or arousal changes. While this assumption has considerable face validity, it seemed worthwhile to investigate the effect of auditory stimulation on the SSEP. Auditory stimuli are one of the most common elements of typical real-world situations in which operator performance must be monitored. It would seem prudent to investigate any potential interference with measures that might be used for monitoring. This experiment was conducted to assess the relationship between auditory noise level and the SSEP.

Method

Six males ranging in age from 27 to 44 years old served as subjects. A schematic diagram showing the functional connections and relationship of the subject to the apparatus is shown in Figure 1.

The steady-state visual stimulus was produced by the pair of fluorescent light tubes and drive circuitry described earlier. The distance from the center of either tube and a translucent surface containing a fixation point (a "plus" character) was .625 in. A vertically mounted 2 X 2 ft. gray board covered the tubes except for a 5-in-square opening at the center through which the subjects viewed the lights. The gray board was 2.625 in. from the surface containing the fixation point, and the subject's eye was 24.625 in. from the board.

The fixation point (0.125 in. square) was centered within the 5-in. opening between the tubes.The fixation point subtended a visual angle of 0.27 deg. at 27.25 in. from the subject's eye. The 5 X 5 in. opening was covered by a ND 0.30 neutral-density Kodak filter. The border around the filter further restricted the opening to 4.5 X 4.5 in., which subtended 10.4 deg. of visual angle at 24.625 in. from the subject's eye. A luminance of 150 fL was measured for 1 deg. of visual angle by a Minolta luminescence meter focused on the fixation point from the subject's eye position. The modulation depth was 30% for each frequency.

The auditory noise was presented over a standard Air Force Astrocom headset. THe noise generator was an HP HOI-3722A set for Gaussian 0-15 kHz noise. The RMS amplitude of the noise was selected to be 65, 75, or 85 dB using a rotating selector. Each rotary setting was calibrated with an octave band noise analyzer and a high-precision microphone. The microphone was located in the same position as the subject's tympanic membrane relative to the headset.

Experimental Procedure

Subjects arrived at the laboratory rested and ready for a 1.5- to 2-hr session. A consent form was read and signed, electrodes were attached, and the subjects were seated before the stimulus display and fit with the earphone headset. Electrodes were removed and reattached if impedances were greater than 5 kohms.

Subjects were directed to be attentive to instructions given by the experimenter prior to each data-collection period. Each period lasted approximately 15 sec, and the data were sampled during the last 10 sec.

In the first and last periods of the session, data were collected with the subject's eyes closed, but with the subjects facing in the direction of the display lights. This procedure provided the control data for artifacts in the EEG record. During all other

data-collection periods, the subjects were asked to fixate on the plus between the two fluorescent tubes while remaining relaxed.

Auditory stimuli levels were 55 (control, no noise generated except for normal room and headset movement noise), 65, 75, and 85 db. Each auditory level was presented at each of the three stimulation frequencies of 45, 48, and 51 Hz in a pseudorandom sequence. Each auditory/frequency combination was given three times for a total of 27 test periods.

Subjects were instructed to look away from the lights or to close their eyes for the 30 sec between periods. Electrode impedance was verified at the end of the session. Some periods were rerun when the subject reported difficulty maintaining the eye fixation throughout the 10 sec of data collection.

Data Manipulation and Statistical Analysis

The Coherence for all trials for each subject was computed and used as a screening tool for eliminating subjects who did not show adequate photic driving. Table 2 shows these values for the six subjects of this experiment. Subject 53 did not show adequate driving (Coherence < .200) and was eliminated from the remaining analyses.

Table 2

Coherences for Each Subject
(Auditory Experiment)

Subject	Coherence
51	.423
52	.872
* 53	.178
54	.841
55	.436
56	.600

* = Eliminated from data analyses because of insufficient driving (Coherence <.200).

Using BMDP, a two-step process was used to produce three RTT values for each decibel level (65, 75, 85 db) for each subject. Initially, a slope from the phase lags at each of the three frequencies for a particular decibel level was computed. For example, to compute the first 65-db slope, the phase lags at the first 45-, 48- , and 51-Hz periods were used. The second 65-db slope was computed from the second 45-, 48-, and 51-Hz periods. The third 65-db slope was computed from the last 45-, 48-, and 51-Hz periods. Finally, the RTT values were produced by dividing

the slopes by 360 degrees. Each RTT value at each decibel level is treated as a trial. The RTT values were analyzed with a typical ANOVA with all variables within subjects, and ANOVAs were computed for each of the subjects with trials as the random variable.

Amplitude, Coherence, and Phase measures from the Fourier analysis of the data were each analyzed by the Analysis of Variance with stimulating frequency and decibel level as within-subject variables.

Results and Discussion

Figure 6 shows the RTT for each subject as a function of auditory intensity. For all subjects as a group, there were no significant differences in RTT as a function of auditory intensity. There also were no significant differences for Coherence, Power, or Phase related to auditory intensity level or the interaction of auditory intensity with stimulation frequency.

Table 3 shows the significance levels reached by the various measures for each subject. Generally, subjects showed differences due to changes in stimulation frequency, but not consistently in the same direction, so the group analysis did not show a significant effect.

Table 3
Significance Levels for Individual Ss
(Auditory Experiment)

SUBJECT	POWER			COHERENCE		
	db	f	db/f	db	f	db/f
51	-	-	-	-	.025	-
52	-	-	-	-	.05	-
54	.05	.01	-	-	.001	-
55	-	.01	-	-	-	-
56	-	.025	-	-	.001	-

db = auditory intensity
f = frequency of stimulation
db/f = interaction between db and f
\- = not significant ($p > .05$)

Figure 7 shows Coherence as a function of stimulation frequency and Figure 8 shows Coherence as a function of auditory intensity for each subject. S51 shows a clear change over frequencies, but in a different direction from the significant changes shown by subjects 52, 54, and 56. It is clear that white noise auditory stimulation does not affect the brain's response to the visual

Figure 6

RTT for each subject as a function

of auditory intensity.

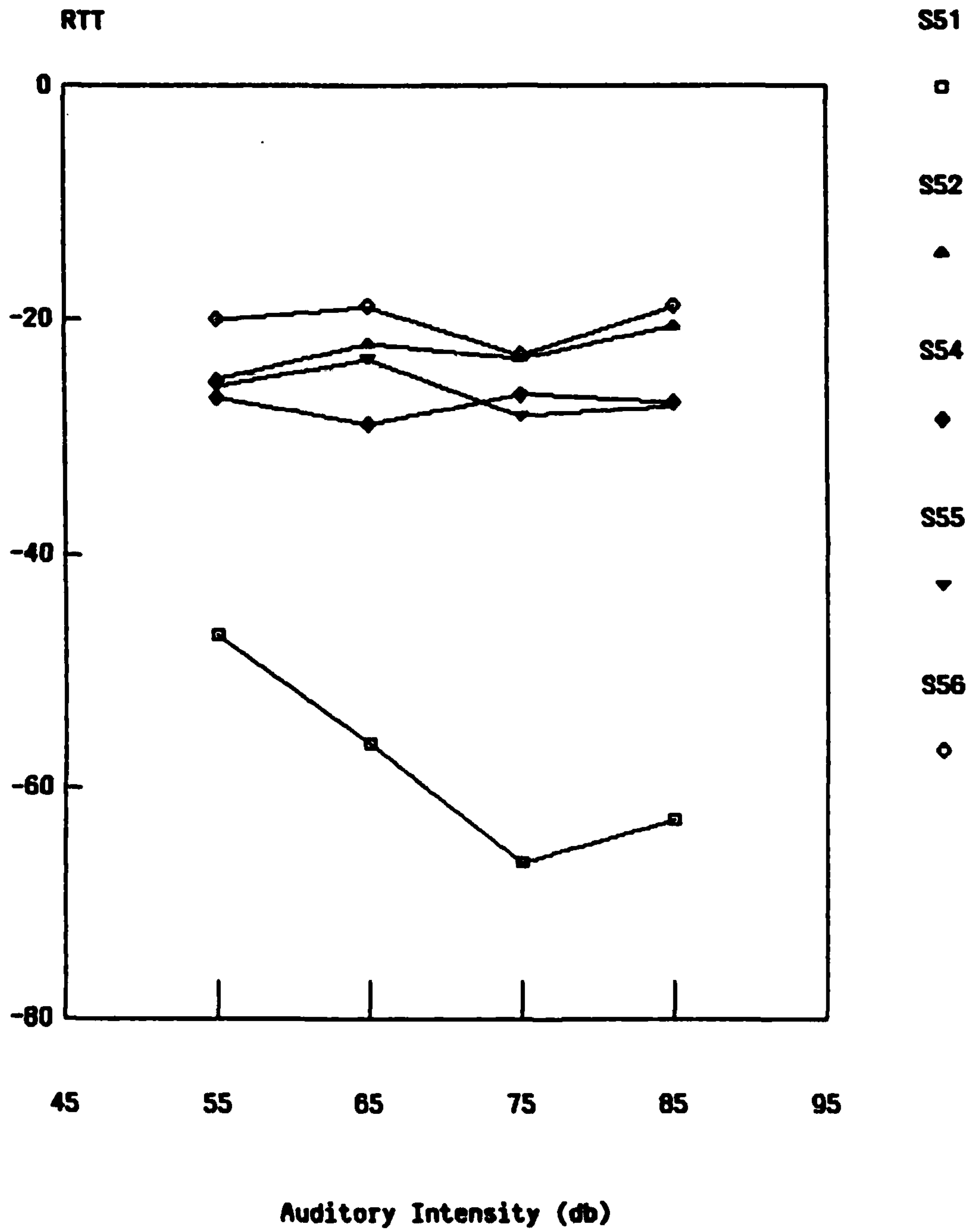


Figure 7. Coherence by stimulation frequency for each subject.

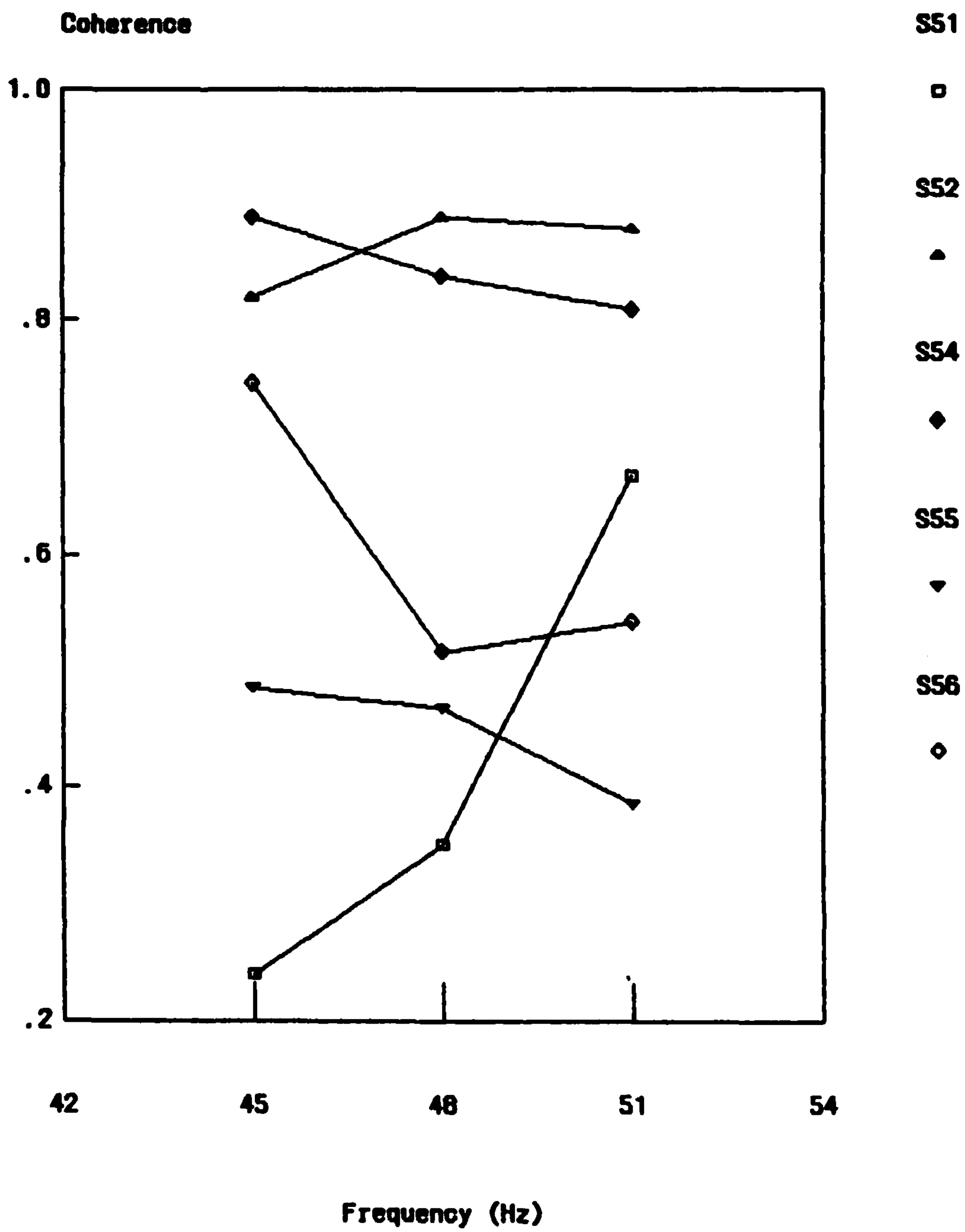
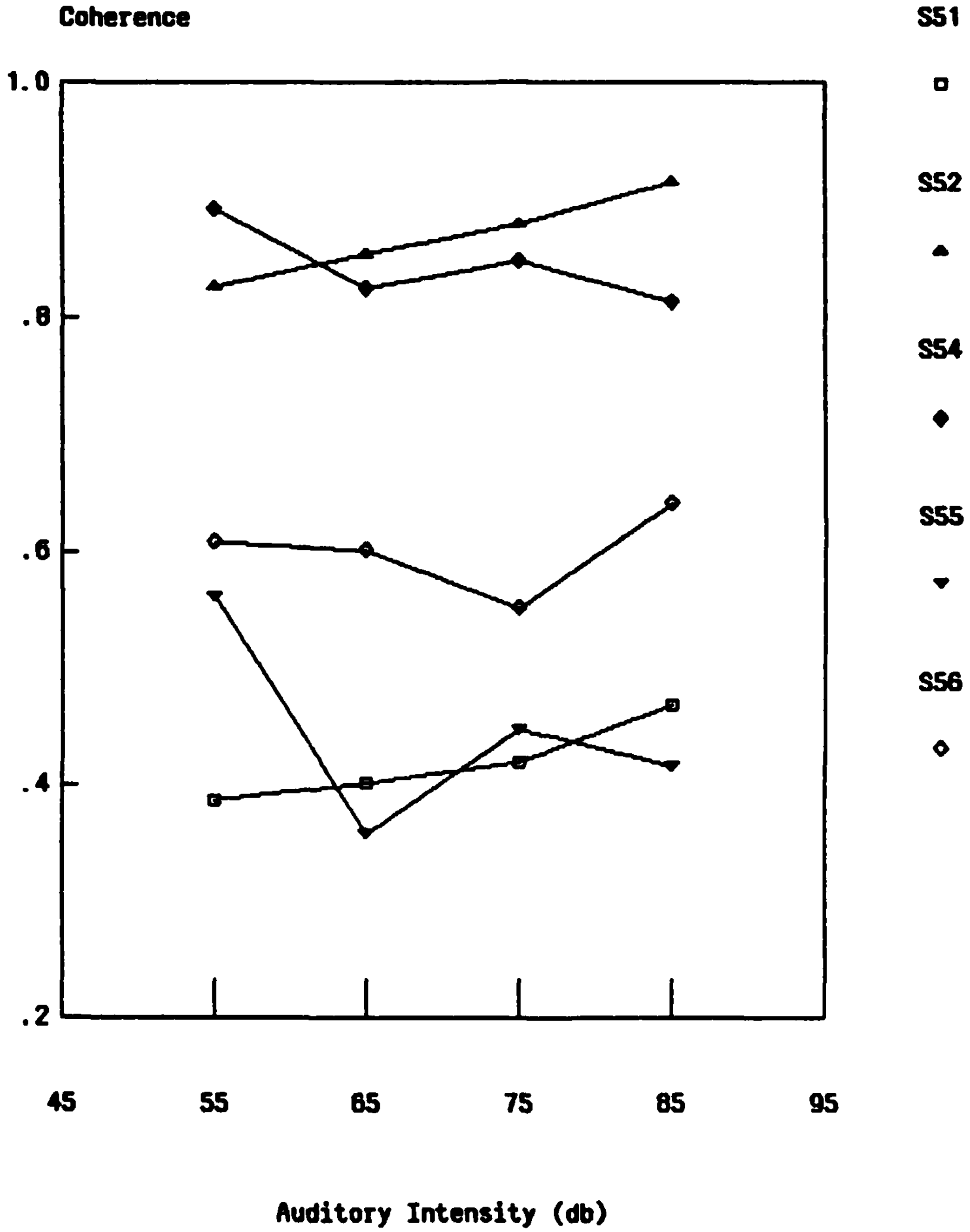


Figure 8. Coherence by auditory intensity level for each subject.



steady-state stimuli we used. Even when analyzed individually, only one subject (54) had a significant change in any measure (Power) as a function of auditory intensity.

In pursuit of the individual differences seen in this and pilot studies, Eddy and Moise (1985) re-evaluated the data of this experiment to demonstrate a single-subject analysis technique on the RTT measure. This detailed analysis of individual subjects revealed that data from two of the six subjects violated the requirement that the RTT be computed from mean phase-lag data that approximate a straight line. It was shown that single subject analysis can provide greater insight into the underlying causes of observed statistical results and that tests of significance for independent tests yield results compatible with the ANOVA.

Color-Brightness Experiment

Studies of color and brightness on evoked potentials have typically been psychophysical investigations designed to examine properties of the visual system. The present experiment used a simple approach to determine in a practical way whether color and intensity changes are reflected in SSEP measures.

Studies of the effect of color on the EP have typically used the transient response with relatively few reports about the effect on SSEP. SSEP studies that do exist often used patterned stimuli, such as checkerboards, instead of the whole field stimulation used in this project.

The psychophysical procedure of heterochromatic flicker photometry has been adapted to include EP recording so as to give objective measures of spectral sensitivity (Regan, 1972). Resulting spectral sensitivity curves have been compared with psychophysical spectral sensitivity curves for the same subject. Peak-to-peak amplitudes of SSEPs in the 10-25 Hz range seem to be of little value as objective measures of spectral sensitivity. However, SSEPs in the 45-60 Hz range can be used to give a spectral sensitivity curve which agrees well with the psychophysical curve (Regan, 1972).

Regan (1970) used a desaturating light flickering onto a colored background to measure how much desaturation was necessary to produce equivalent amplitude SSEPs to different colored stimuli.

Neuroscience Technology International, in a project for the Westinghouse Corporation (1979), used a flickering white light stimulus on different colored backgrounds to measure SSEP amplitude and phase response to different colors.

In most of these studies, reflected rather than transmitted light reached the eye. Since transmitted light is effective in generating SSEPs, the present experiment used an arrangement in

which clear fluorescent tubes flickered behind colored filters so that colored light is transmitted, rather than reflected to the eye.

If high-frequency SSEP components show spectral sensitivity, it is important to investigate whether this will add complexity to the use of SSEPs as measures of performance. Frequently operational environments have color stimuli to which operators must attend and respond in the performance of their tasks. In addition, if the SSEP is sensitive to particular color and intensity combinations, use of these measures could be useful in evaluating equipment design.

Method

Six males and one female ranging in age from 27 to 44 years old served as subjects. A schematic diagram showing the functional connections and relationship of the subject to the apparatus is shown in Figure 9.

The steady-state visual stimulus was produced as described in the Auditory study with the addition of a color filter in front of the intensity filter for producing colored light, and additional neutral density filters as needed to adjust brightness. Modulation depth for each frequency and color combination was 20%.

The color filters were made by Kodak (mfg. nos. 47, 58, 29, 9, 96). These were used in conjunction with Kodak neutral density filters of .1, .2, and .3 (the proportion of light blocked by each filter, Kodak mfg. no. 96) in order to adjust luminance to the desired levels. Table 4 lists the colors and brightnesses used in the study.

Table 4
Colors and Brightnesses in the Color/Brightness Experiment

COLOR	DOMINANT WAVELENGTH (Angstroms)	BRIGHTNESS (Foot Lamberts)
BLUE	463.8	5
GREEN	540.3	20
RED	631.6	70
YELLOW	574.3	150
CLEAR	ALL	

It was not possible to adjust all colors to all levels of brightness as some darker colors would not pass adequate light to reach the brighter levels. Therefore the data was treated in

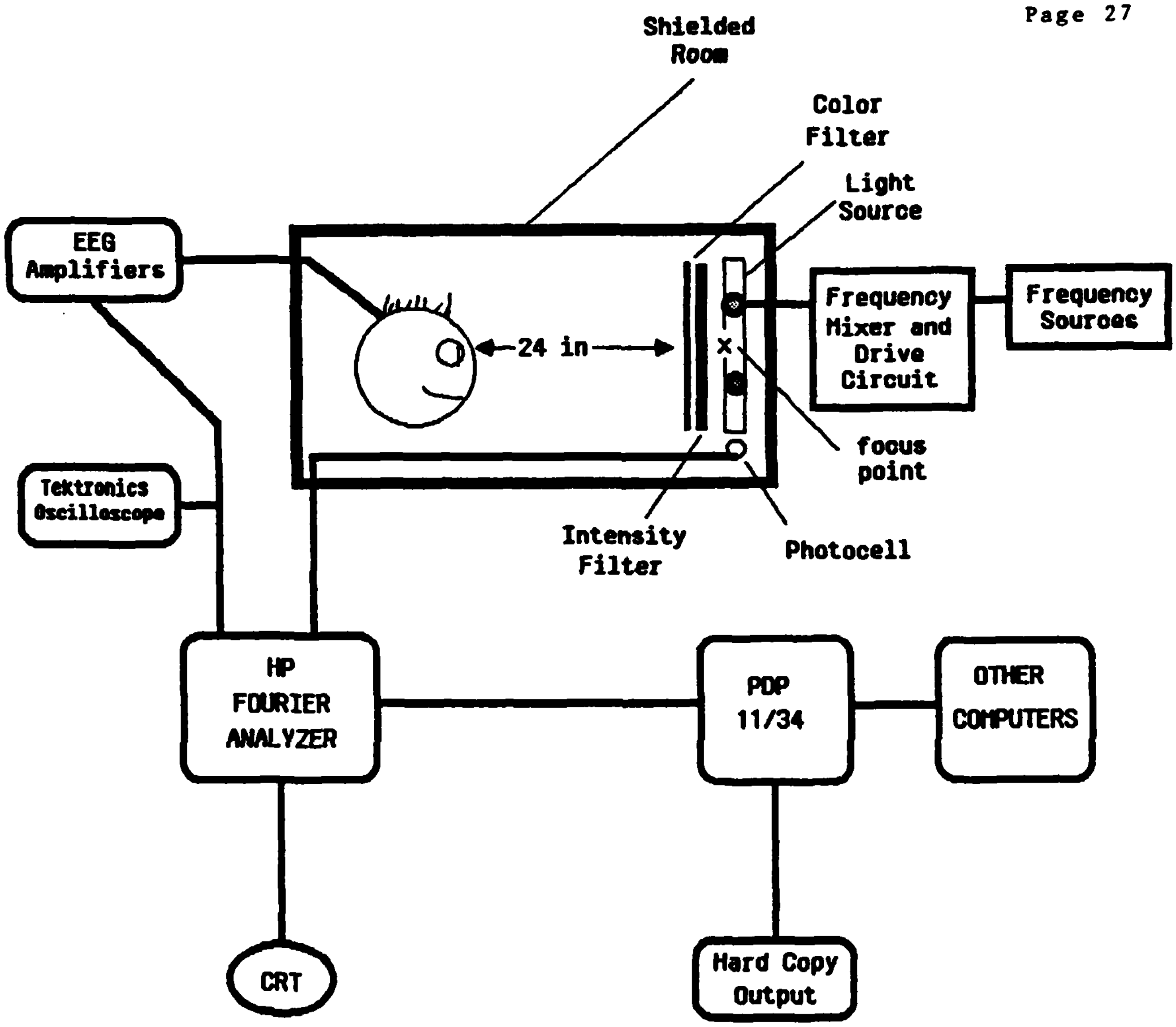


Figure 9. A schematic diagram of the subject and apparatus.
(Color-Brightness Experiment)

Brightness (ftl)		Colors 1 (Blue)	2 (Red)	3 (Green)	4 (Yellow)	5 (Clear)
	5	X	X	X	X	X
	20		X	X	X	X
	70			X	X	X
	120				X	X

C4-5/B1-4

C3-5/B1-3

C2-5/B1-2

C1-5/B1

Table 5

Groupings of colors and brightnesses for analysis.

groups of equal brightness. Table 5 shows the combinations used for analysis.

The EEG was captured as described earlier. A program in the Fourier analyzer computed the average power spectra for each signal and the average cross-power from 10 1-sec epochs. The sample rate was 256 per second. The phase lag, the transfer function, and the coherence were computed then forwarded to a DEC PDP-11/34 computer for storage and data reduction. The data were then moved to a PDP-11/70, where they were processed with the BMDP and SAS statistical packages.

Experimental Procedure

Subjects arrived at the laboratory rested and ready for a 2- to 2.5-hr session. A consent form was read and signed, electrodes were attached, and the subjects were seated before the stimulus display. Electrodes were removed and reattached if impedances were greater than 5 kohms.

Subjects were directed to be attentive to instructions given by the experimenter prior to each data-collection period. Each period lasted approximately 15 sec, and the data were sampled during the last 10 sec.

In the first and last periods of the session, data were collected with the subject's eyes closed, but with the subjects facing in the direction of the display lights. This procedure provided a control for possible artifacts in the EEG record. During all other data-collection periods, the subjects were asked to fixate on the plus between the two fluorescent tubes while remaining relaxed.

In order to minimize the problems of the eye adapting to different brightnesses, the data for each color and frequency combination was collected for a given brightness as a block. The order of colors and frequencies was randomized within a brightness block. After the set of all brightness blocks was presented and recorded, a second and third set were presented. The order of the brightness blocks within a set was randomized as well as the order of the colors and frequencies within the brightness blocks.

Subjects were instructed to look away from the lights or to close their eyes for the 30 sec between trials. Electrode impedance was verified at the end of the session. Some periods were rerun when the subject reported difficulty maintaining the eye fixation throughout the 10 sec of data collection.

Data Manipulation and Statistical Analysis

The Coherence for all trials for each subject was computed and used as a screening tool for eliminating any subjects who did not show adequate photic driving. Table 6 shows these values for the seven subjects of this experiment for each color-brightness analysis. As in all studies, subjects whose overall Coherences were below .200 were not included in the analyses.

Using BMDP, a two-step process was used to produce an RTT value for each color-brightness combination for each subject. Since there were three trials at each of three frequencies, nine phase lag values were used to determine the best fitting straight line for each color-brightness combination. The RTT values were computed by dividing the slope by 360 deg. RTT values, using the groupings of Table 5 for all subjects, were analyzed with an ANOVA with all variables within subjects.

Table 6
Coherences for Each Color/Brightness Group

		GROUP			
		C1-5/B1	C2-5/B1-2	C3-5/B1-3	C4-5/B1-4
S	57	.227	.361	.555	.603
U	58	.150*	.151*	.250	.338
B	59	.385	.461	.538	.551
J	60	.210	.302	.398	.437
E	61	.515	.579	.687	.720
C	62	.134*	.174*	.239	.198*
T	63	.106*	.122*	.145*	.181*

* = Coherence is below required minimum (.200). This subject's data is not included in the analysis for this group.
C = Color (1=blue, 2=red, 3=green, 4=yellow, 5=clear).
B = Brightness (1=150 ftl, 2=70 ftl, 3=20 ftl, 4=5 ftl).

Amplitude, Coherence, and Phase measures from the Fourier analysis of the data were each analyzed by an ANOVA with brightness, color, and stimulating frequency as within-subject variables.

Results

There were no significant effects or trends in the RTT as a function of color, brightness, frequency of stimulation, or their interactions.

Figure 10 shows power of the SSEP as a function of brightness level for each color/brightness combination for all subjects. Although the general trend is for an increase in power with increasing brightness, there were no significant main effects for power due to brightness in any of the color/brightness analyses.

Figure 10. Power (microvolts) by brightness (foot lamberts) for each color/brightness combination.

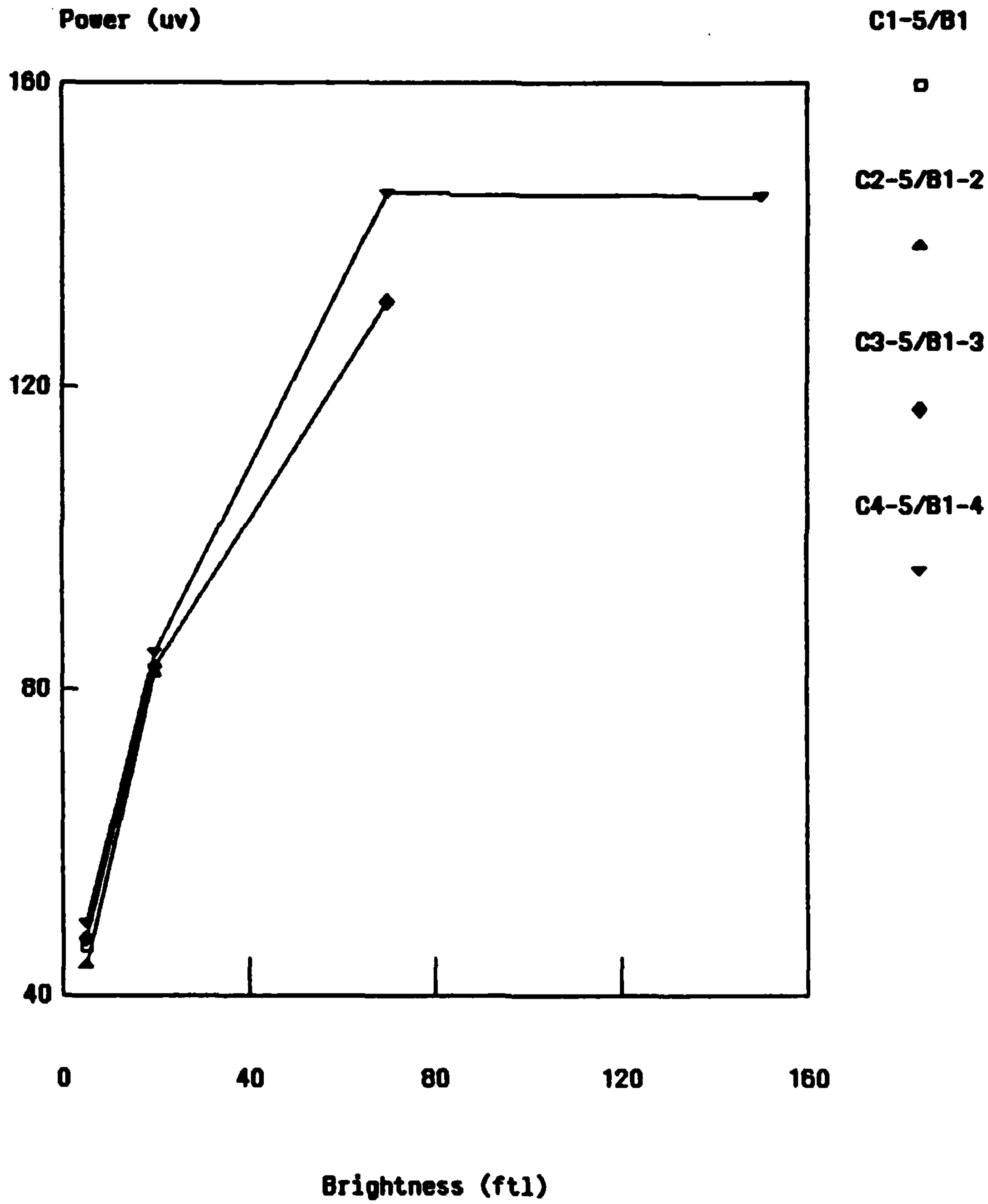


Figure 11 shows power of the SSEP as a function of color for each color/brightness combination for all subjects. Within each color/brightness group there were no significant main effects due to color. It is interesting to compare the individual curves (Figure 12) with the group curves for this data. Subject 57 consistently showed higher power than the other subjects, and in the C1-5/B1 and C2-5/B1-2 analyses showed a significant difference over color ($F=10.719$, $df=3/6$, $p<.01$ and $F=5.592$, $df=4/8$, $p<.025$ respectively) which is largely due to a relatively large response to yellow.

Power decreased somewhat from the lower to higher stimulation frequency (Figure 13). This was more evident for yellow and clear colors and showed a significant difference ($F=6.011$, $df=2/8$, $p<.05$) for yellow-clear (C4-5/B1-4).

The next three graphs show the same relationships for coherence. In Figure 14, it is clear, and not very surprising, that coherence increased as brightness increased. These increases were significant for C2-5/B1-2 ($F=99.258$, $df=1/3$, $p<.005$), C3-5/B1-3 ($F=26.021$, $df=2/10$, $p<.001$) and C4-5/B1-4 ($F=25.095$, $df=3/12$, $p<.001$). Since C1-5/B1 has only a single data point, no test of significance for this variable is possible.

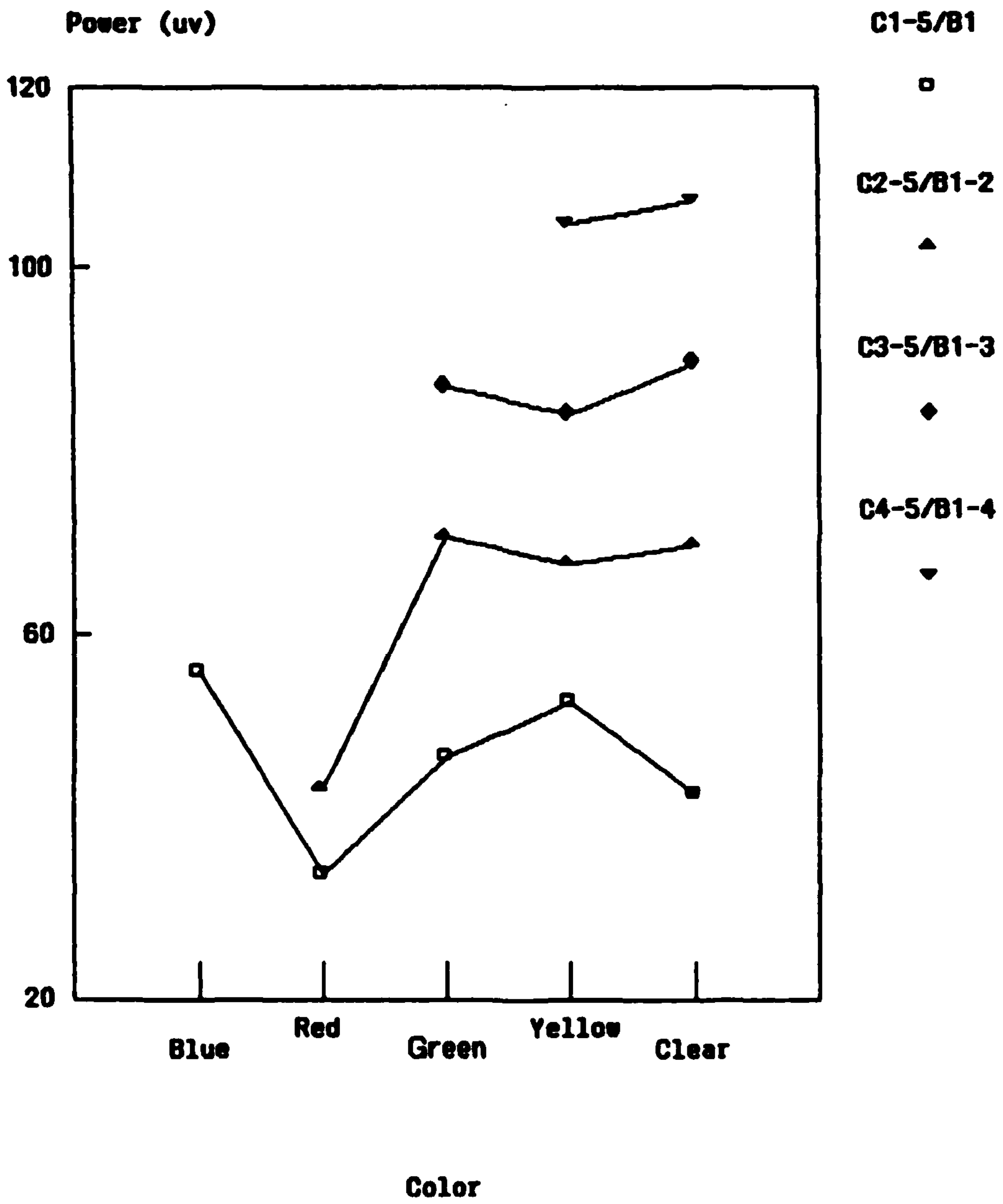
Figure 15 shows the coherence as a function of color. The observed differences are significant for C1-5/B1 ($F=17.581$, $df=4/12$, $p<.001$), C2-5/B1-2 ($F=12.794$, $df=3/9$, $p<.005$), and C3-5/B1-3 ($F=8.747$, $df=2/10$, $p<.01$). Only C4-5/B1-4 was not significant. As one might expect, there is not much difference between yellow and clear colors.

In spite of the overall levels of significance shown by coherence, T-test comparisons between pairs of colors revealed few significant differences. T-tests were significant between blue and red colors for C1-5/B1 ($T=2.471$, $df=6$, $p<.048$) and between red and green for C2-5/B1-2 ($T=2.808$, $df=6$, $p<.03$). These are the only color/brightness combinations in which red is present. From Figure 15 it may be seen that coherence for red is lower than for other colors. In fact, for C1-5/B1, the value for red drops below our nominal criteria for satisfactory driving (criteria = coherence $>=$ .200, actual value for red = .187).

This is particularly interesting in the light of an oral presentation by Dr. June Scully at the Human Factors meeting in San Antonio (November, 1984). Dr. Scully reported difficulty obtaining SSEPs in a B52 field study in which the test area aboard the aircraft was illuminated with a red light. The data presented here suggests that their difficulty with the SSEP may have been partially due to an inability to produce adequate driving with (or in) red light.

There were no significant differences in Coherence as a function of frequency (Figure 16). The literature on SSEP frequency

Figure 11. Power (microvolts) by color for each color/brightness combination.



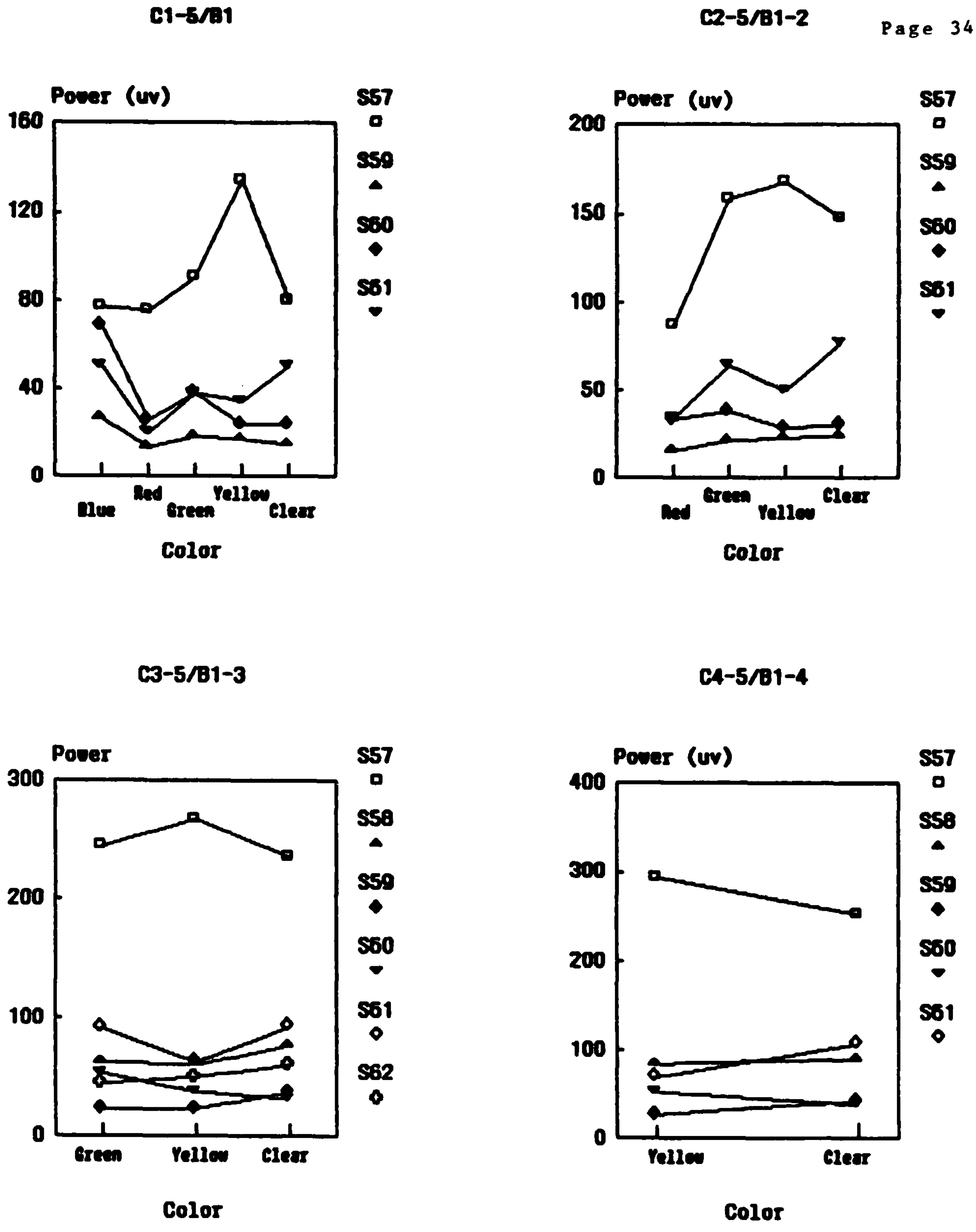


Figure 12. Power (microvolts) by color for each subject in each color/brightness condition. In these graphs the data are collapsed over brightness.

Figure 13. Power (microvolts) by stimulus frequency for each color/brightness combination.

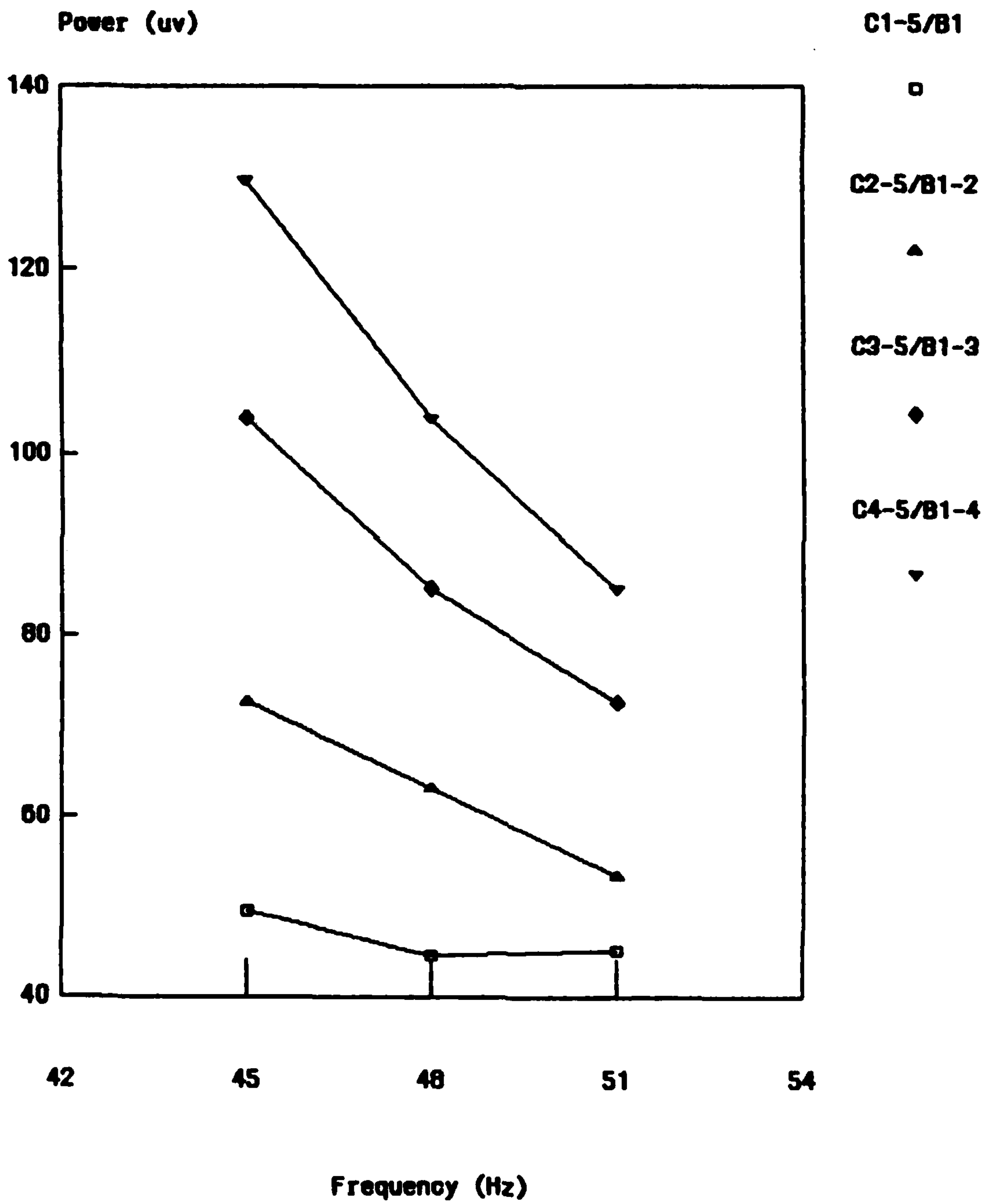


Figure 14. Coherence by brightness for each color/frequency combination.

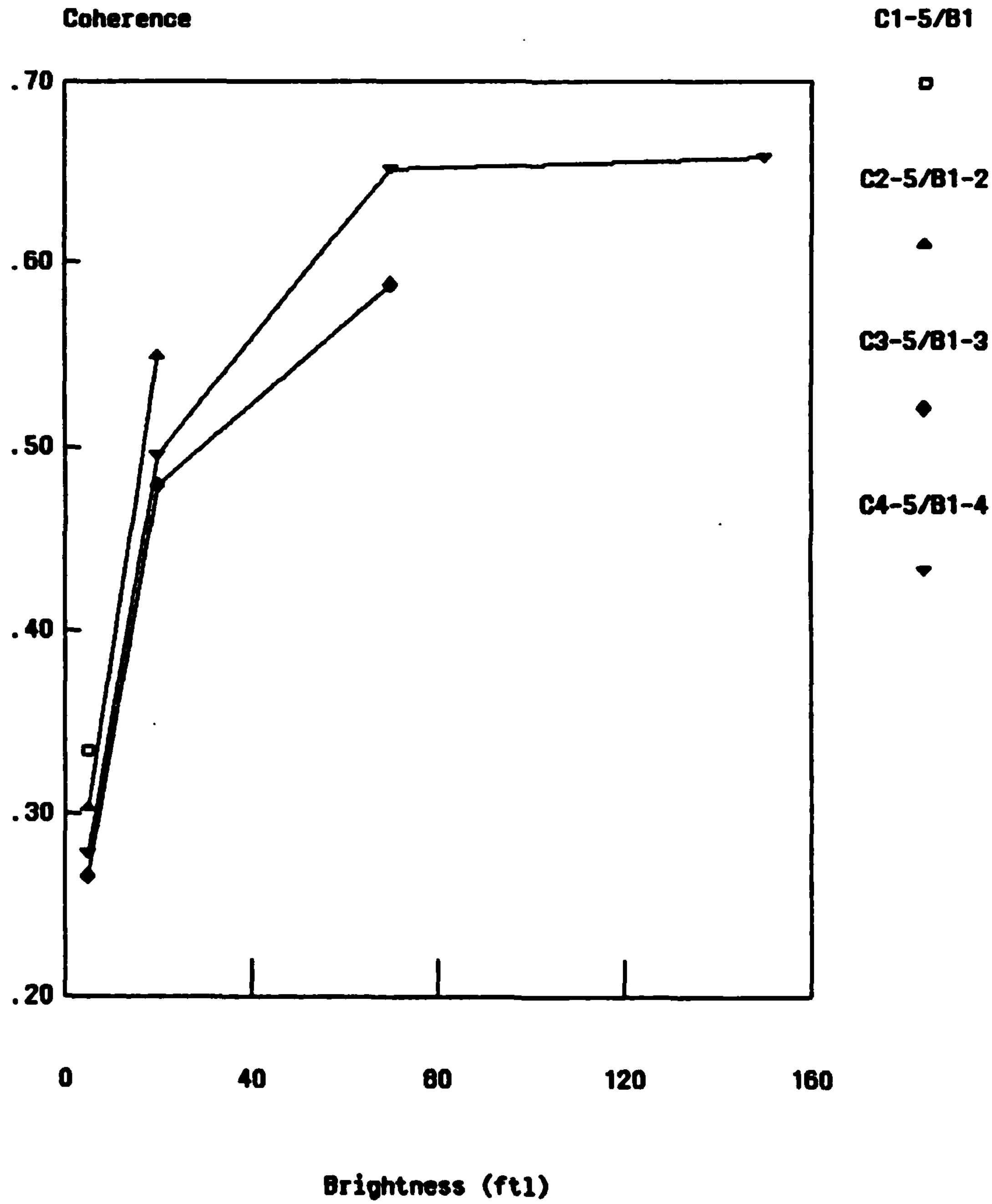


Figure 15. Coherence by color for each color/brightness combination.

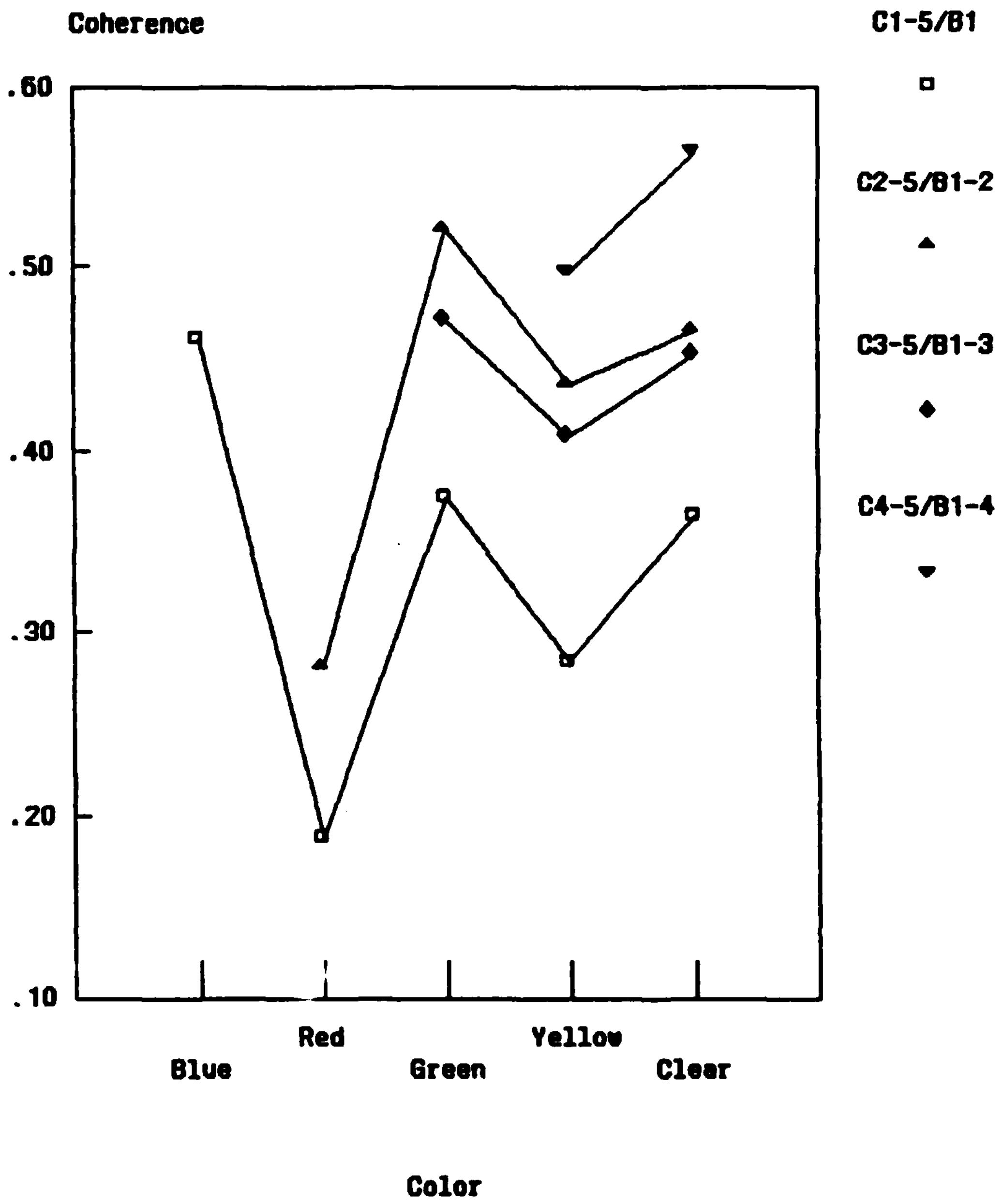
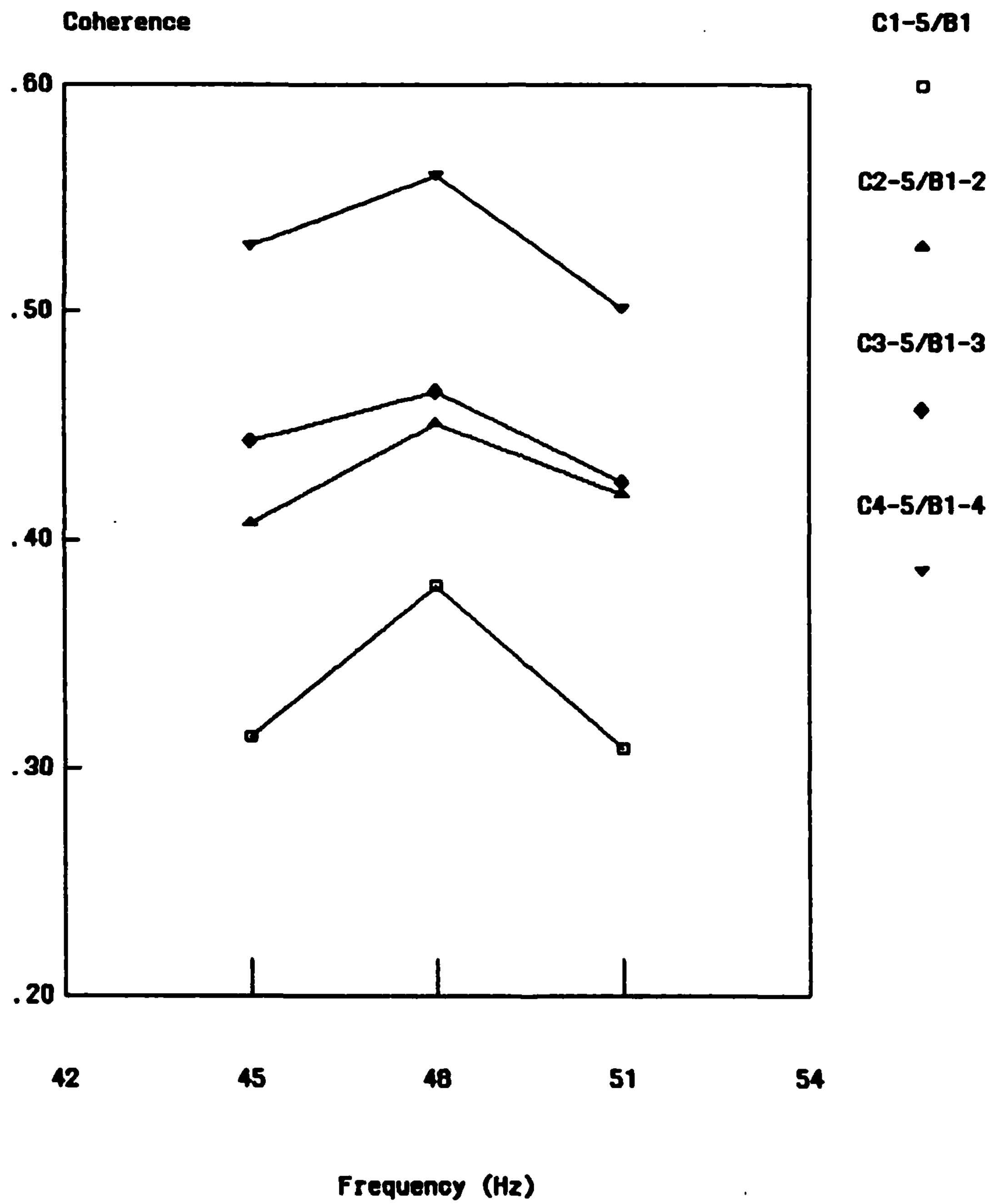


Figure 16. Coherence by frequency for each color/brightness combination.



responses might lead one to speculate that we would see our subjects respond more actively to one frequency than another. This was not generally the case as there was only one (marginally) significant difference over frequencies for either power or coherence measures. It is encouraging, if surprising, that the use of different frequencies did not result in overall differences in the brain's ability to track the driving stimulus.

Phase relationships showed no significant differences as a function of brightness or color, but show some differences as a function of frequency (C2-5/B1-2 $F=7.986$, $df=2/6$, $p<.025$; C3-5/B1-3 $F=8.407$, $df=2/10$, $p<.01$; C4-5/B1-4 $F=8.670$, $df=2/8$, $p<.025$). Figure 17 shows the individual subject plots for these effects. Milner, Regan, and Heron (1974), in a study of effects of multiple sclerosis on SSEPs, show a graph (their Figure 29.4) which shows the phase from a normal control subject. Phase for this subject increases as frequency of stimulation increases over the high (38-54 Hz) range. Even though they used pattern reversal SSEPs, their phase changes and range of phase lags match the values we found very well.

There were no significant interactions between color and brightness for power, coherence, or phase in any analysis.

Discussion

There are no directly compatible reports in the literature with which to compare our whole field stimulation of transmitted colored lights at different brightnesses. In the present study, power did not show significant increases as brightness increased, although there was a distinct trend in that direction. The coherence measure did show clear and significant increases as brightness increased. Phase lags did not change as a result of brightness increases.

Regan (1972) summarized psychophysical studies of SSEPs to selective chromatic adaptation by suggesting that the evoked potential contains components of different spectral sensitivities. The data showing this consists of phase shifts for different colors.

Using an adaptation of standard heterochromatic flicker photometry, SSEP recordings have yielded objective measures of spectral sensitivity. Peak-to-peak amplitudes of SSEPs in the 10-25 Hz range are not useful for measuring spectral sensitivity. However, SSEPs in the 45-60 Hz range can be used to give spectral sensitivity curves which agree well with curves obtained with standard psychophysical techniques.

Regan summarizes with the statement that the picture resulting from research is complex. Part of this complexity is likely that EPs to colored stimuli reflect neural activities not directly related to color perception.

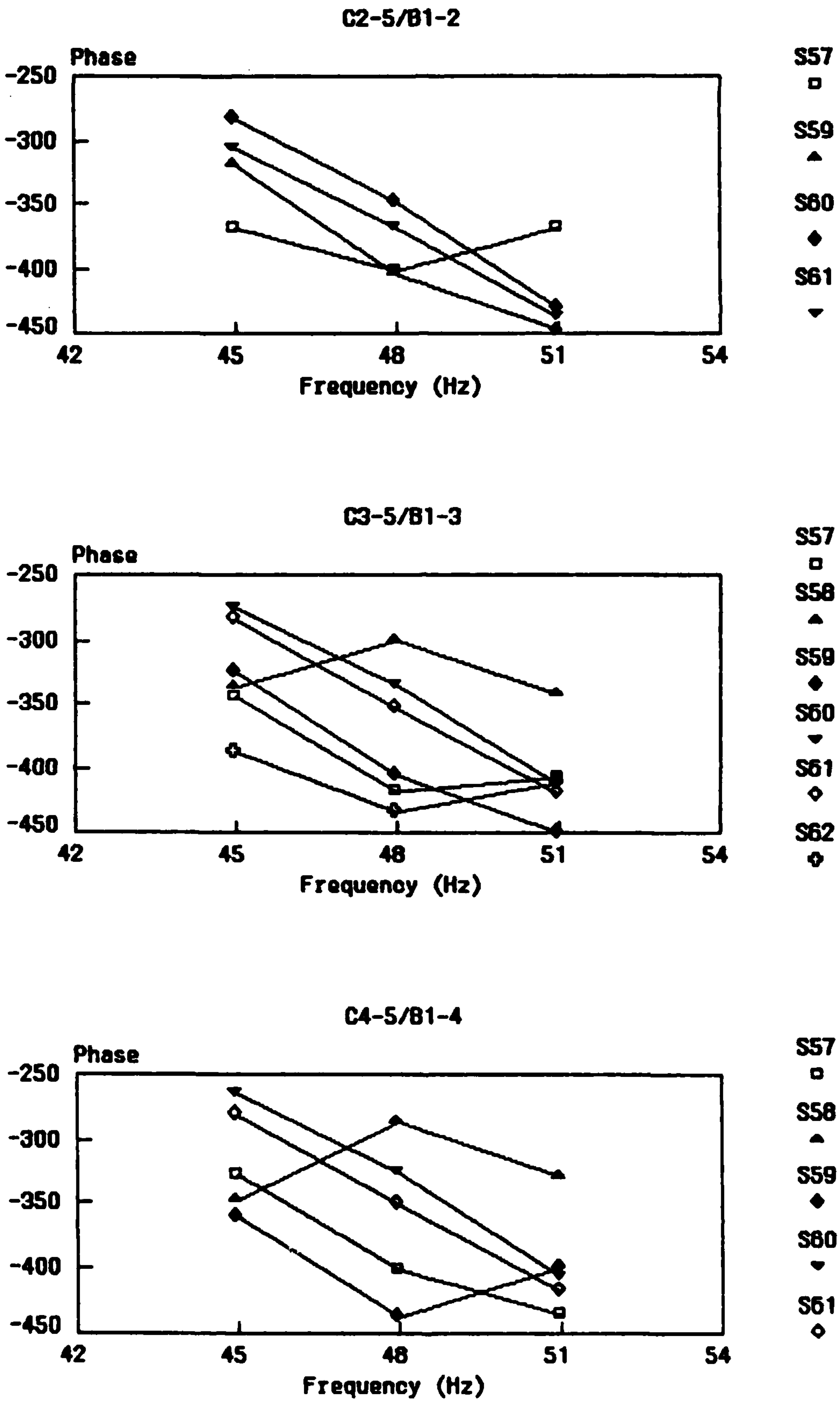


Figure 17. Phase Lag by frequency for each color/brightness combination.

Regan further points out that it is essential to demonstrate that effects are due to specific stimulus colors and not to either luminance effects or photopic-scotopic phenomena. In the present experiments, the use of whole-field stimuli with a central focal point effectively eliminated photopic-scotopic effects.

We have accounted for intensity effects by presenting color stimuli at a variety of different intensities. Regan correctly pointed out that it is not enough to present different colors whose intensity have been adjusted as subjectively equal. It is essential to include observations over a range of intensities to conclude that observed effects are not due solely to intensity.

Unlike most psychophysical experiments, the present studies used transmitted rather than reflected colored light and no desaturating lights. In our data there were no significant differences in power due to color for any combination of brightnesses. The coherence measure however, did reveal color differences in all but one brightness condition (the brightest). For those analyses in which red appeared, the brain showed low levels of driving compared to other colors. There were no significant brightness/color interactions and it appears that for these data, color and intensity do not combine in any detectably synergistic way.

In summary, the coherence measure seems to be the most sensitive measure of brightness and color differences and should be seriously considered whenever these variables must be detected or monitored.

Tracking Experiments

In this set of experiments the RTT and other SSEP measures were investigated in a performance task in order to discover the SSEPs utility for monitoring performance in a complex task environment. In addition, we wanted to investigate these measures under fatigue and rested conditions. Discussions with members of the Crew Performance Function at Brooks, revealed an interest in the effects of 24hr fatigue performance effects. This would provide them with data that could be of use in other research on flight crew performance during 24 hour missions.

Instead of running several experiments to investigate these various effects, we decided to design one composite study that combined a tracking task with performance measured at various points over an 18 hour period.

The performance task used in this experiment was the Cross-Coupled-Instability Task (CCIT) (Jex and Clement, 1979; Jex, Jewell, and Wade, 1973). The following description is adapted from the paper by Jex and Clement (1979).

This task was conceived to provide a secondary control-type task which could load an operator in a manner similar to the secondary control axes in a multi-degree-of-freedom task. The CCIT is a closed-control single-axis tracking task which uses an unstable controlled element (the object to be tracked) having an adjustable first-order divergence. The level of instability of the divergence is increased rapidly at first, and then gradually, until the operator loses control. This defines the "Critical Instability" (lamda). This parameter has been found to be very stable for a given combination of display, control, and operator. An operator can track continuously at some "sub-critical" level of lamda less than his critical level for the given control-display combination, and his describing function parameters can be measured and modeled very well.

Method

Six males ranging in age from 25 to 45 years old served as subjects. A schematic diagram showing the functional connections and the relationship of the subject to the apparatus is shown in Figure 18.

The steady-state visual stimulus was produced as described in the Auditory study except that the flickering light reached the subject after reflection by a beam splitter. The beam splitter was a half-silvered mirror which transmitted 50% of the light falling on it and reflected the other 50%. The tracking display reached the subject by transmission from a CRT through the beam splitter. In this way a flickering light stimulus was superimposed on the tracking display.

The tracking task was generated and controlled by the Cross Coupled Instability Task (CCIT), Model 9769A from Systems Technology Inc., Hawthorne, California. The CCIT ground support unit (Systems Technology, Inc.) provided 28V DC power to the CCIT computer. The tracking console on which the tracking task was presented was a rack-mounted CRT from Computer Image Corporation.

A NEC PC-8201A computer with 16k RAM and 32k ROM was used as a terminal to the CCIT tracking computer to initiate data collection and setup. The NEC then collected and buffered the data from the CCIT as it ran the tracking task. The data was then transmitted from the NEC over a RS232 serial interface to a PDP 11/34 computer.

The vertical channel on the tracking CRT was used to present a vertical line as the tracking element. This bar was generated by a Hewlett Packard 3310A function generator (Model #1151A05480).

The EEG was captured as described earlier. A program in the Fourier analyzer computed the average power spectra for each signal and the average cross-power from 10 1-sec epochs. The sample rate was 256 per second. The phase lag, transfer function,

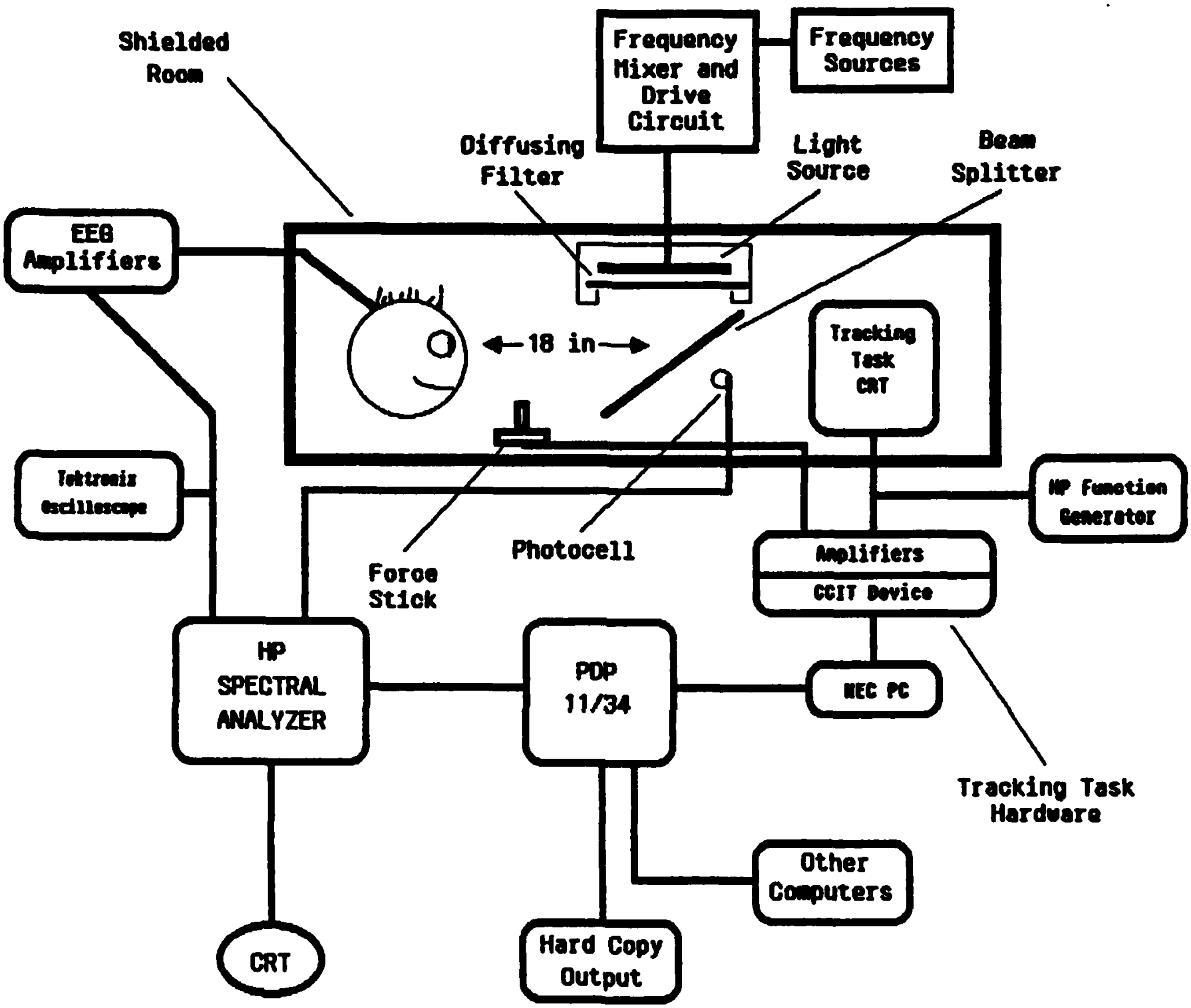


Figure 18. A schematic diagram of the subject and apparatus.
(Tracking Experiment)

and coherence were computed then forwarded to a DEC PDP-11/34 computer for storage and data reduction. The data were then moved to a PDP-11/70, where they were processed with the BMDP and SAS statistical packages.

EEG data were monitored in real-time with a Tektronix Oscilloscope.

The tracking Force Stick was mounted in the center of a table which was 18 3/4" X 23 5/8" in area, and 31" high. The stick was pressure sensitive, not movable, and was manufactured by Measurement Systems, Inc. (Model #435M5151DC).

Experimental Procedure

Training

All subjects were trained for 3-5 days over a 1-2 week period prior to data collection. Consent forms were read and signed by each subject prior to the start of the first training session. Subjects had the opportunity to end their participation in these experiments at any time.

During training, subjects attempted to hold the unstable cursor on the top of a fixed pointer. Lamda, the instability parameter, gradually increased until the cursor was forced off the screen, no matter how skillfully the subject attempted control.

The value of lamda at the time of loss-of-control was the value which quantified maximum workload. Subjects were trained until asymptotic levels of performance were achieved.

Testing

On the day of testing, subjects arrived at the laboratory at 07:00 hours, rested and ready to participate in a 22 hour experiment.

Tracking and data collection sessions took place at 08:00, 14:00, 20:00, and 02:00 hours. Subjects performed normal work or other activities, including eating meals at the usual times, between testing sessions.

At the start of each testing session, electrodes were attached and the subjects were seated before the stimulus display. Electrodes were removed and reattached if impedances were greater than 5 Kohms. Each testing session lasted from 1.5 to 2 hours.

Testing began with the subject completing five adaptive trials identical to training. The median lamda was recorded as the maximum workload value. Then 50%, 30%, and 10% levels of difficulty were computed by multiplying lamda by .5, .3, and .1.

These values were keyed into the CCIT computer for presentation of the trials. Each subject, therefore, worked at a load which was either .5, .3, or .1 of his own maximum.

Each testing trial began and quickly adjusted to the lamda level selected for that trial. In trials with lamda=0 (no tracking), subjects watched the fixation point for the duration of the trial, but did no tracking. Each tracking trial lasted 50 seconds. The data collection period began 30 seconds after the subject began tracking and terminated 10 seconds later (10 seconds before the end of the trial).

In each testing session two trials of data were collected for 4 workload levels and three stimulation frequencies for a total of 24 trials. There was approximately one minute between trials. In addition, there were three trials of no flickering stimulation at each of the four workload levels. This was a grand total of 36 trials for each subject for each of the four sessions.

Electrode impedances were verified at the end of each session.

In order to independently assess fatigue over the duration of the testing period, all subjects answered a subjective fatigue questionnaire, a crew status fatigue checklist, and had their oral temperature taken. The subjective fatigue and crew status checklists are included in the Appendix.

Data Manipulation and Statistical Analysis

The data from subject 65 was lost during his session and this subject was not used in any of the performance or SSEP analyses.

Coherence for all trials for each subject was computed and used as a screening tool for eliminating any subjects who did not show adequate photic driving. Table 7 shows these values for the five subjects with complete data. As in all these studies, any subject whose overall coherences were below .200 would not have been included in further analyses of SSEPs.

Table 7
Coherences for Each Subject
(Tracking Experiment)

SUBJECT	COHERENCE
66	.457
67	.401
68	.621
69	.402
70	.515

Using BMDP, a two-step process was used to produce an RTT value for each tracking load-time condition. Since there were two trials at each of three frequencies, six phase lag values were used to compute the best fitting straight line for each load-time combination. RTT values were produced by dividing the slopes by 360 degrees. RTT values for all subjects were analyzed by an ANOVA with all variables within subjects.

Amplitude, Coherence, and Phase measures from the Fourier analysis of the data were each analyzed by the ANOVA with time of day, workload (Lamda), and frequency of stimulation as within-subject variables.

Results and Discussion

Figure 19 shows the average oral temperatures for each test period. The differences in temperature were significant over time of day ($F=21.111$, $df=3/15$, $p<.001$). This overall difference is primarily accounted for by the difference between temperature at 20:00 and 02:00 hours ($T=3.878$, $df=10$, $p<.003$).

Figure 20 shows the average subjective fatigue scores. For this measure, a low score indicates greater perceived fatigue. The difference in scores over time is significant ($F=4.962$, $df=3/15$, $p<.025$). This main effect is due to the significant differences between each of the time periods and 02:00 hours (see table 8).

In like manner, Figure 21 shows the average crew status checklist results. For this measure, higher scores indicate increased perceived fatigue. The difference was significant ($F=13.185$, $df=3/15$, $p<.001$) and was accounted for by the differences between each time period and 02:00 hours (08:00 - 02:00, $T=4.719$, $df=10$, $p<.008$; 14:00 - 02:00, $T=8.944$, $df=10$, $p<.000004$; 20:00 - 02:00, $T=4.791$, $df=10$, $p<.0007$).

All of these measures are as expected. Oral temperature rises in the early evening and then falls to its lowest point when the subject has been up at least 19 hours since arriving at the lab at 07:00. Both subjective fatigue measures confirm that the subjects perceived themselves as significantly more tired at the 02:00 hour session than at any time before. In fact, these scores indicated that subjects perceived themselves as equally alert and capable at all earlier sessions. This could be due to a lack of sensitivity of these scales although the SSEP data described below agreed with these results.

When data from all subjects are considered together, there are no significant differences in any performance or SSEP measure. Careful examination of individual's data showed that the subjects separated into two groups. Ss 66, 68, and 70 had similar performance and SSEP patterns while Ss 67 and 69 appeared to have random data. We were not surprised at this kind of individual variation given the results already reported, but still wished to

Figure 19. Oral temperature at each testing session.

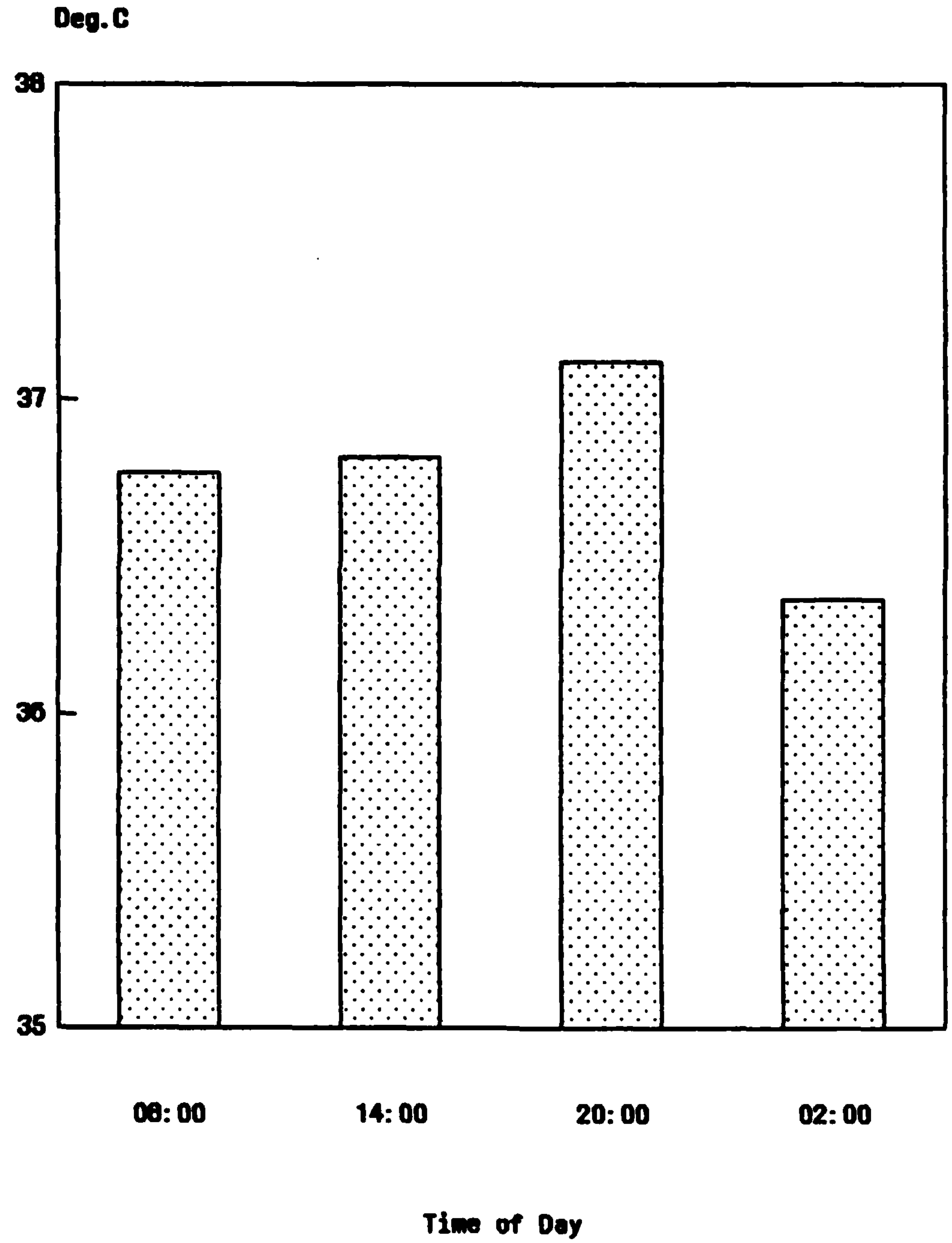


Figure 20. Subjective Fatigue scores at each testing session.

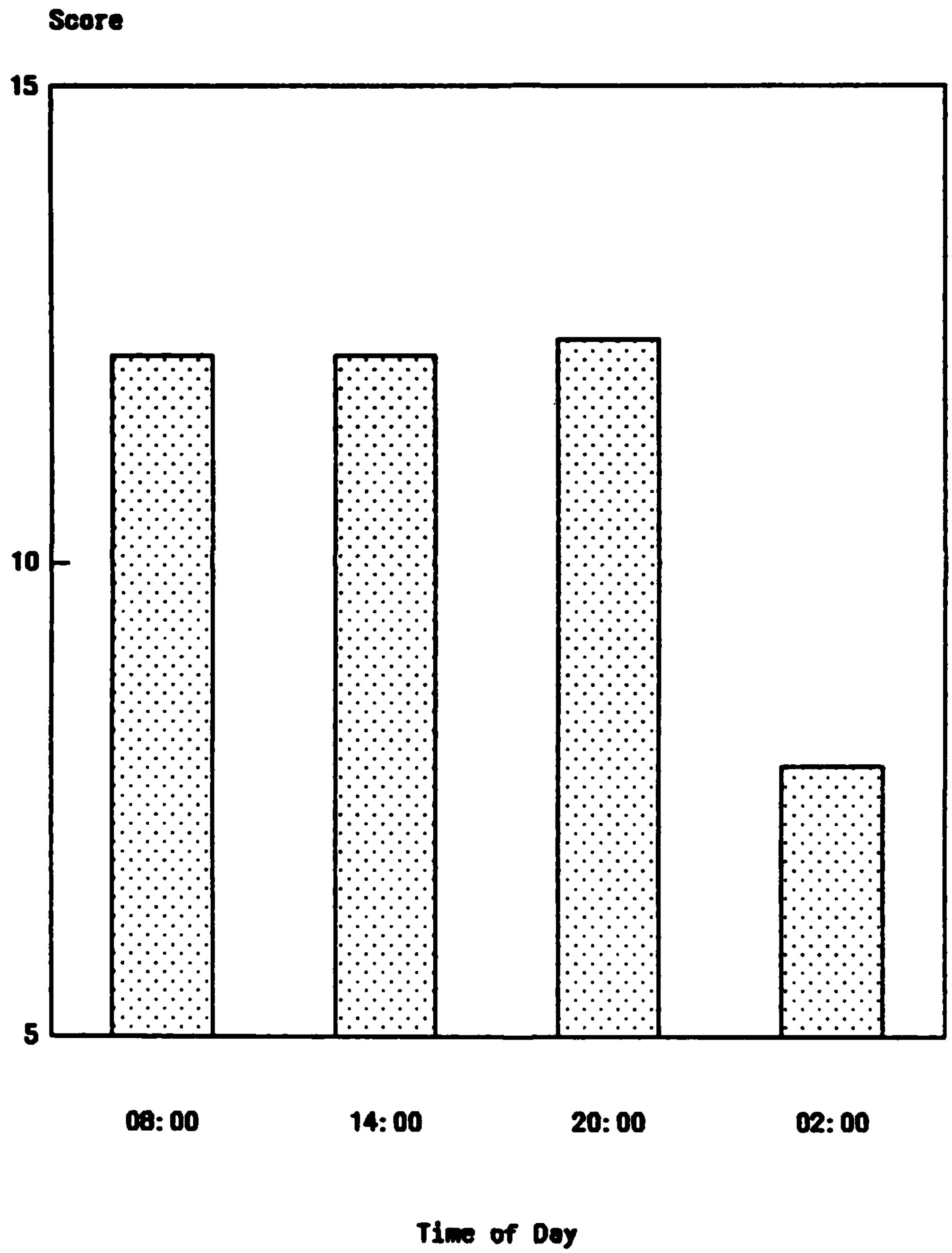
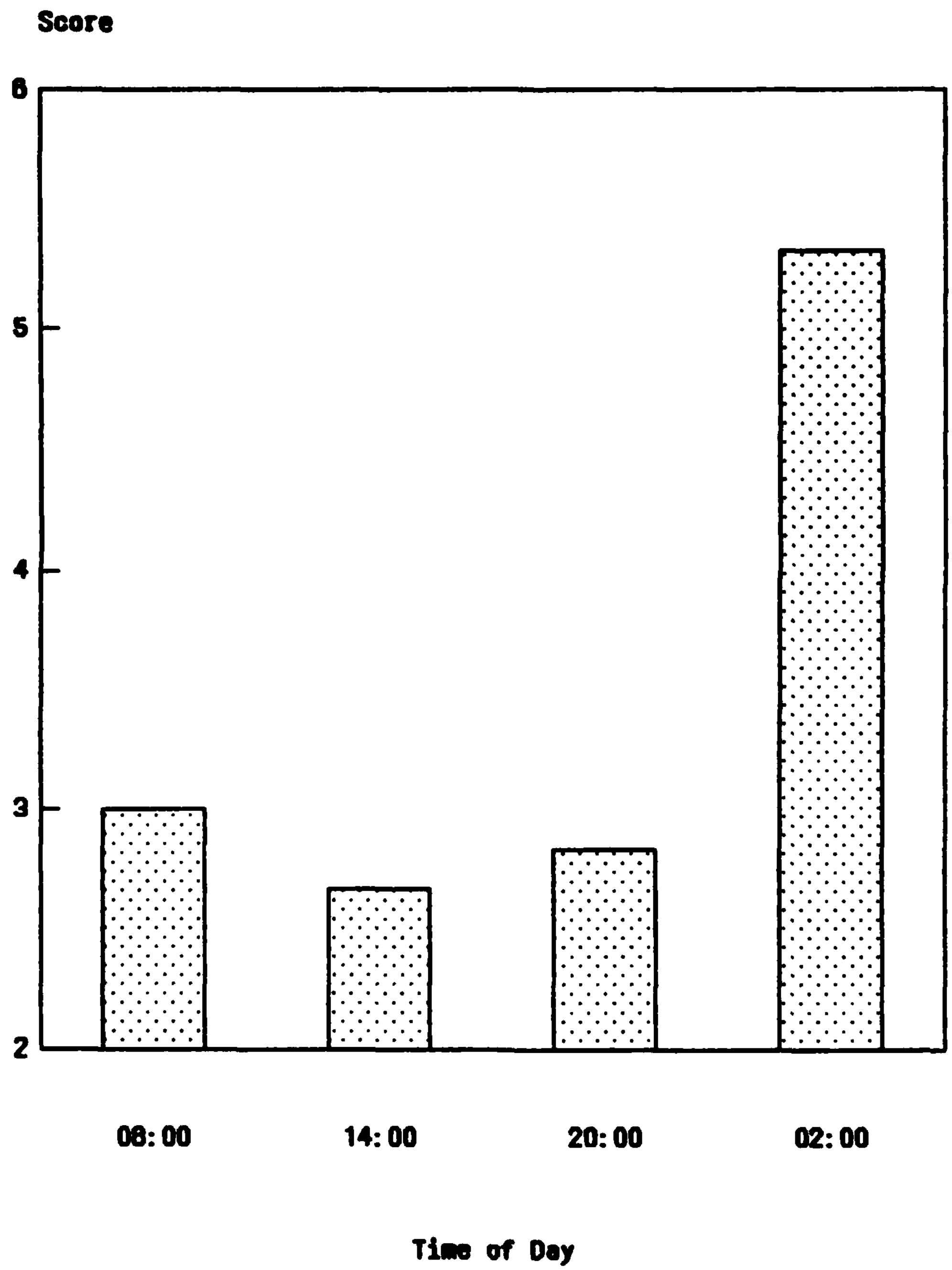


Figure 21. Crew Status Checklist scores at each testing session.



examine group effects in our attempt to find generalizable results. Therefore, we proceeded with an analysis of the group of three similar subjects.

Table 8
Significance Levels
(Subjective Fatigue Measure)

Time Periods Compared	p	df	T
08:00 - 14:00	1.000	10	0.000
08:00 - 20:00	.925	10	0.009
08:00 - 02:00	.005	10	3.591
14:00 - 20:00	.914	10	0.111
14:00 - 02:00	.005	10	5.099
20:00 - 02:00	.014	10	2.985

Performance Measures

Several performance measures are computed by the CCIT test system. These include Lamda (the final level of task difficulty when performance broke down), EC (Excess control Capacity, an index of workload margin), and E (an error measure). EC is an inverse measure so that higher scores indicate reduced excess capacity, indicating increased workload. Unfortunately, due to technical difficulties, the E measure was not analyzed and is not reported here. It will be possible to eventually recover this data and any publications resulting from this work will include the E measure.

Since Lamda was a manipulated variable in these experiments (to produce the various workload levels) it was not appropriate for analysis here. All performance variables are closely related to workload level and so were not analyzed as a function of workload, but as a function of time of day and frequency of stimulation.

Figure 22 shows the change in Excess Control Capacity over time of day. There is a significant change over time of day ($F=10.440$, $df=3/6$, $p<.01$). There is little change over the first three testing periods, but a dramatic change in the final period when the subjects perceived themselves as most fatigued. EC changed in the expected direction, indicating that the subjects were acting as if workload had increased significantly.

In addition, EC showed a significant change in the interaction between workload and time of day ($F=3.292$, $df=9/18$, $p<.025$; Figure 23). Naturally, the 0 workload control condition was significantly different from all other workload conditions and is omitted from Figure 23. This interaction is due to the greater increase in EC over time of day for higher workload conditions. For example, the highest workload condition (WL 5) showed a

Figure 22. Excess Control Capacity by time of day.

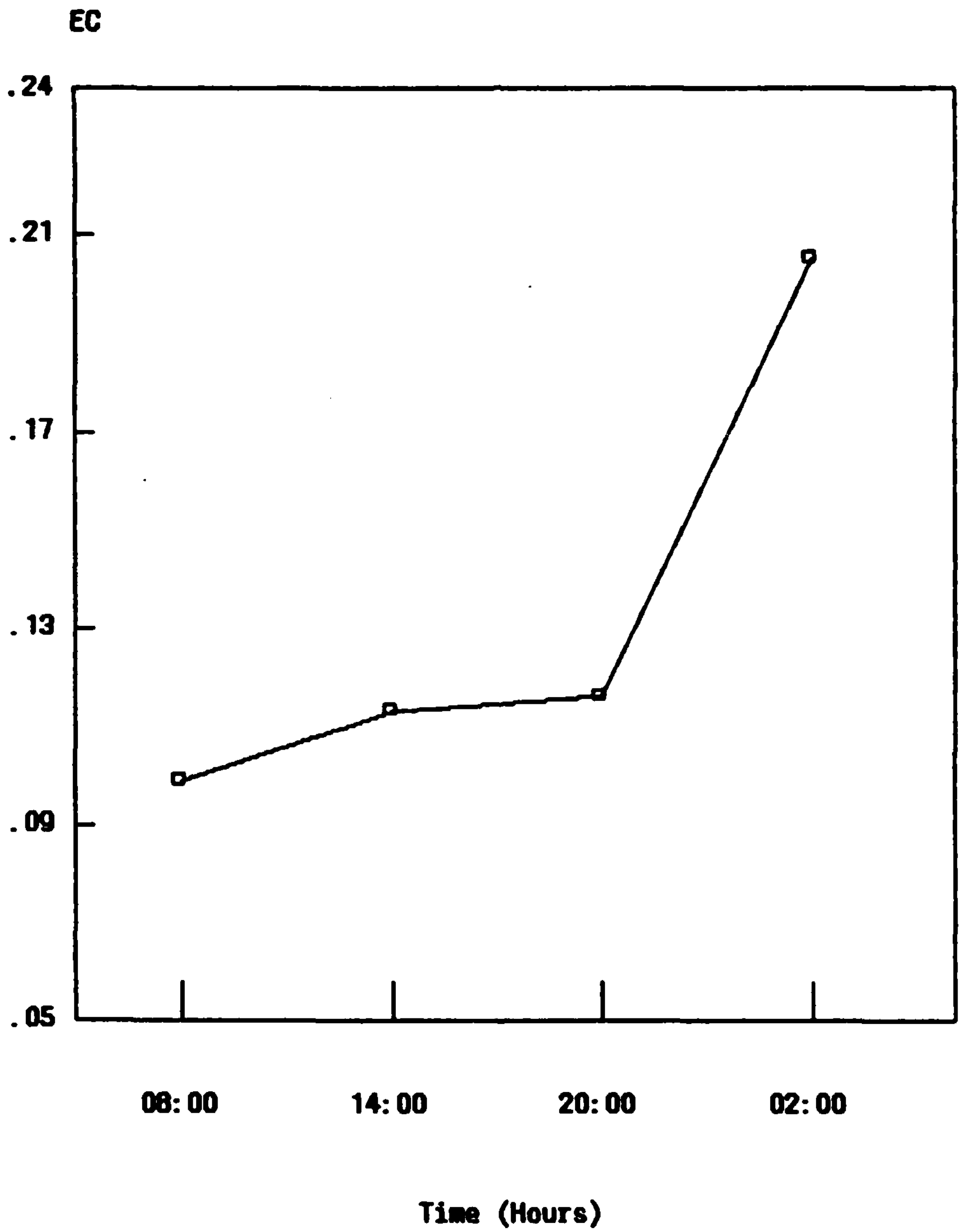
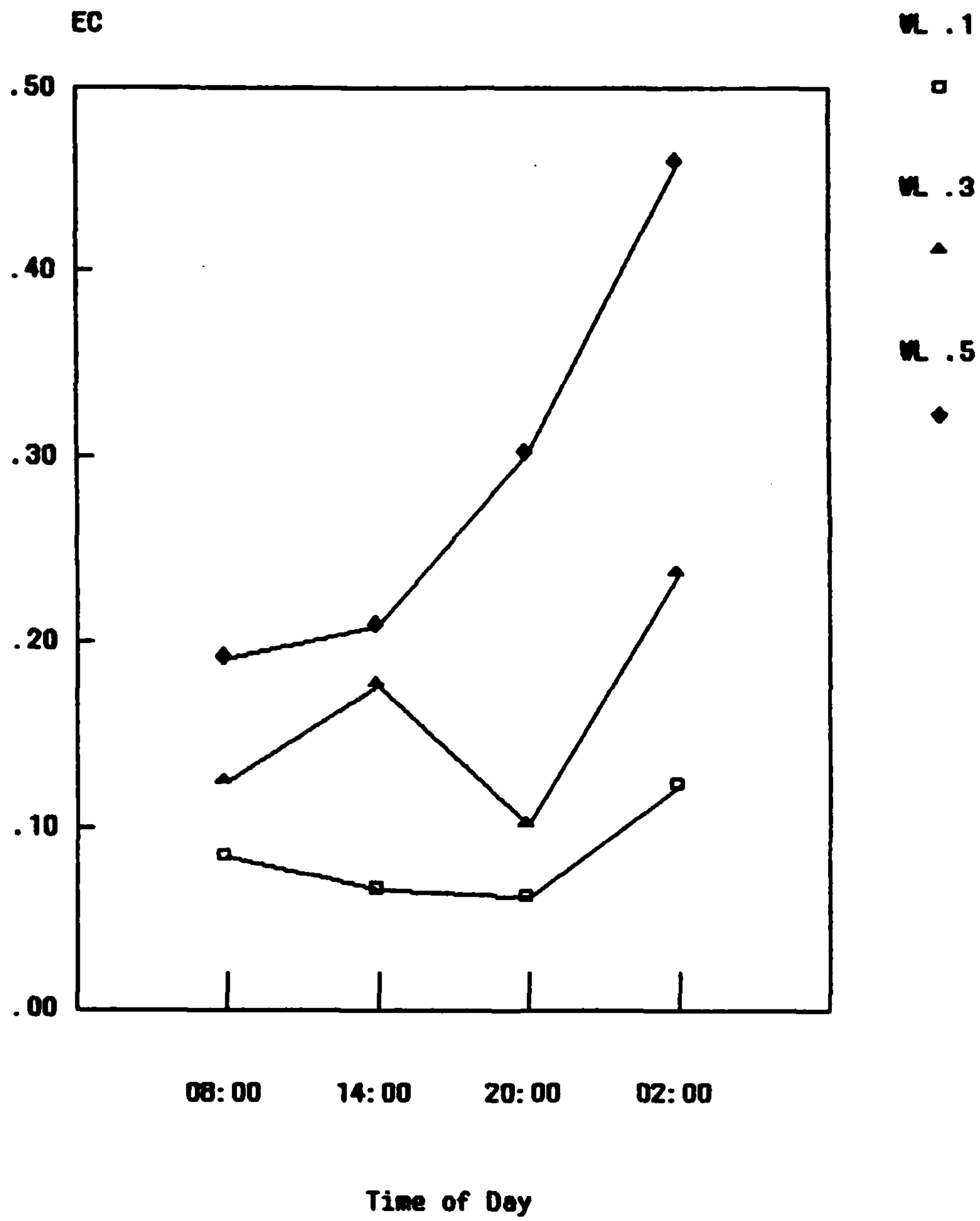


Figure 23. Excess Control capacity (EC) by time of day for 3 workload conditions (1=easy, 3=medium, 5=difficult).



significantly higher EC at 02:00 hours than in any other workload/hour combination (Ts>4.633, df=4, $p<.01$).

In general, the EC measure matched the subject's perception of their own fatigue. Workload increased when the subjects were fatigued, especially if the task was difficult.

SSEP Measures

There were no significant effects or trends for the RTT as a function of any independent variable or interaction between these variables.

Power was significantly different over frequency of stimulation as shown in Figure 24. There is a small but significant decrease in power ($F=9.304$, df=2/4, $p<.05$) with increasing frequency.

Coherence changed significantly with workload ($F=6.561$, df=3/6, $p<.05$; Figure 25). It is interesting that coherence was at its lowest at .3 load instead of the most difficult level (.5). This was a weak effect and T-Tests between workload levels did not show significant differences.

Phase changes were significant for frequency of stimulation ($F=11.250$, df=2/4, $p<.025$; Figure 26), the interaction between Frequency and Time of Day ($F=3.370$, df=6/12, $p<.05$; Figure 27), and the interaction between Frequency and Workload ($F=4.220$, df=6/12, $p<.025$; Figure 28).

As in the Color-Brightness study, phase lag increased with increasing frequency of stimulation and was similar in slope and range to those reported for normal subjects (Milner, Regan, and Heron, 1974).

The interaction between phase lag and time of day is due to the nonlinearity of curves at 08:00 and 02:00 hours. These are the most rested and most fatigued testing periods. These are compared with the relatively linear curves at 14:00 and 20:00 hours.

The significant interaction between frequency and workload is primarily due to the linear relationship between frequencies in the 0 (no workload) condition compared to the nonlinear responses caused by reduced phase lag at 51 Hz when some level of workload is present. While not significant by the T-test, it may be that 51 Hz phase relationships are sensitive to the presence of a task the subjects must perform.

Overall Discussion

The RTT as presented and computed in this research is not a useful measure of either the brain's response to color and brightness, or to fatigue and performance variables.

Figure 24. Power by stimulation frequency for each subject.

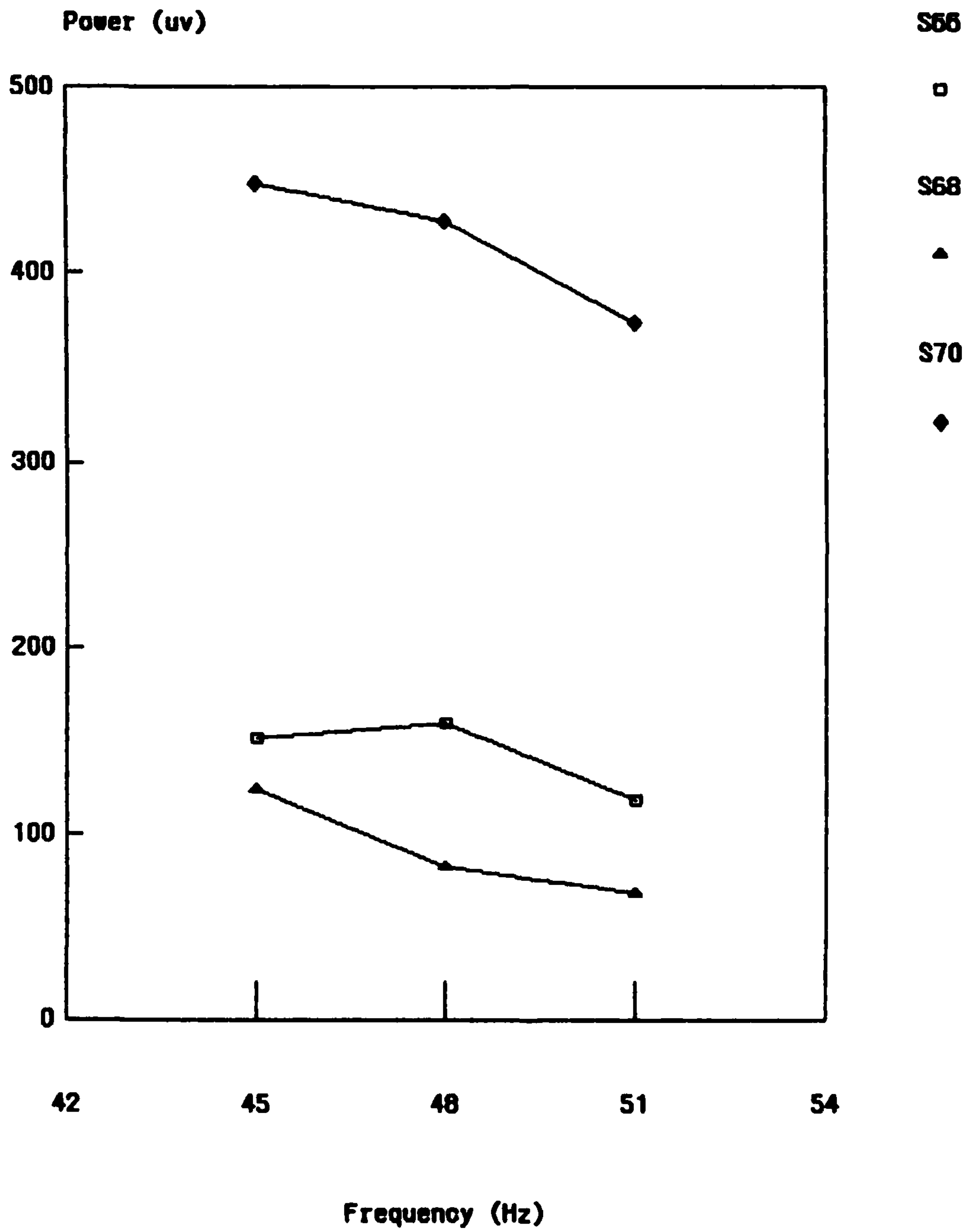


Figure 25. Coherence by workload.

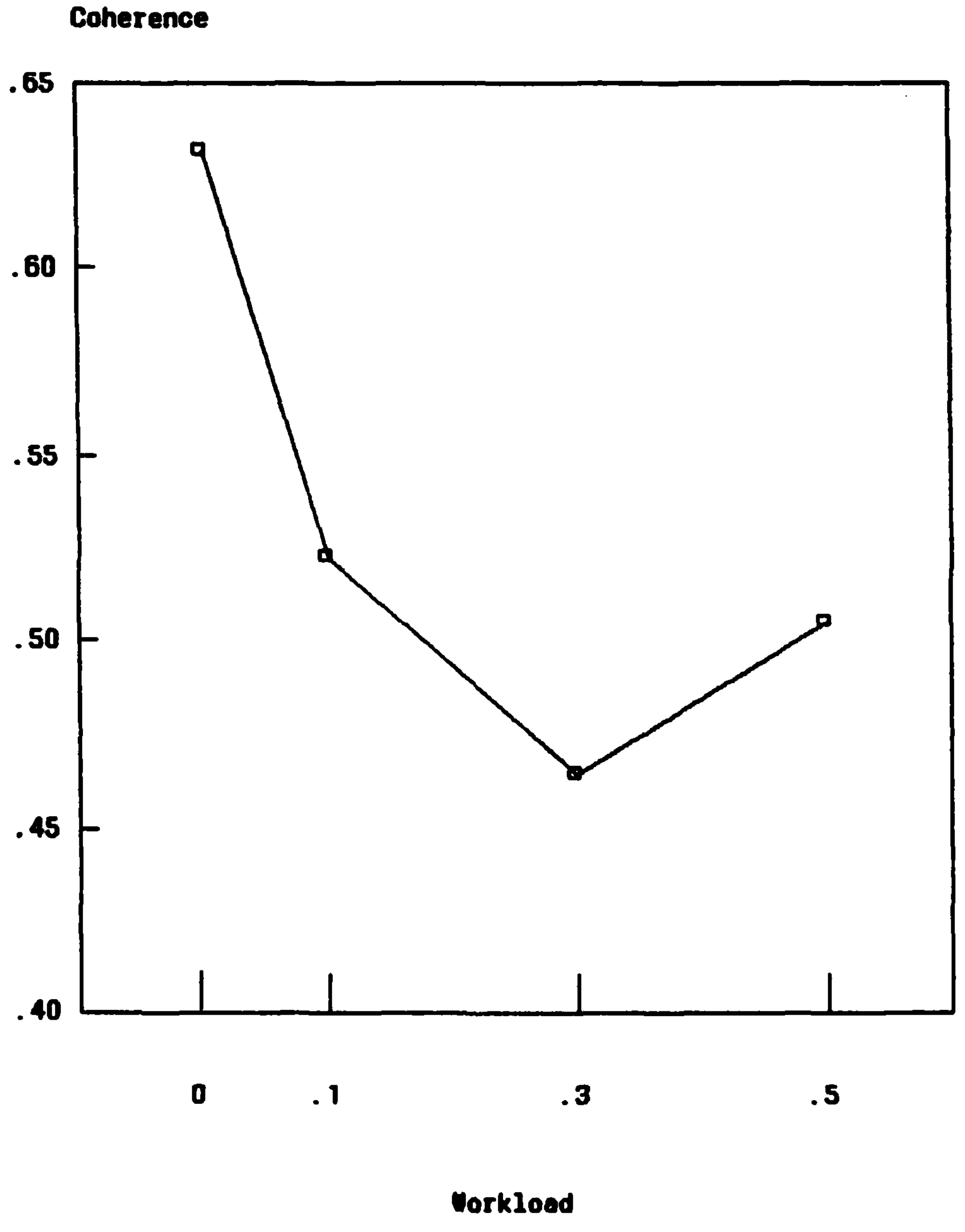


Figure 26. Phase by frequency of stimulation.

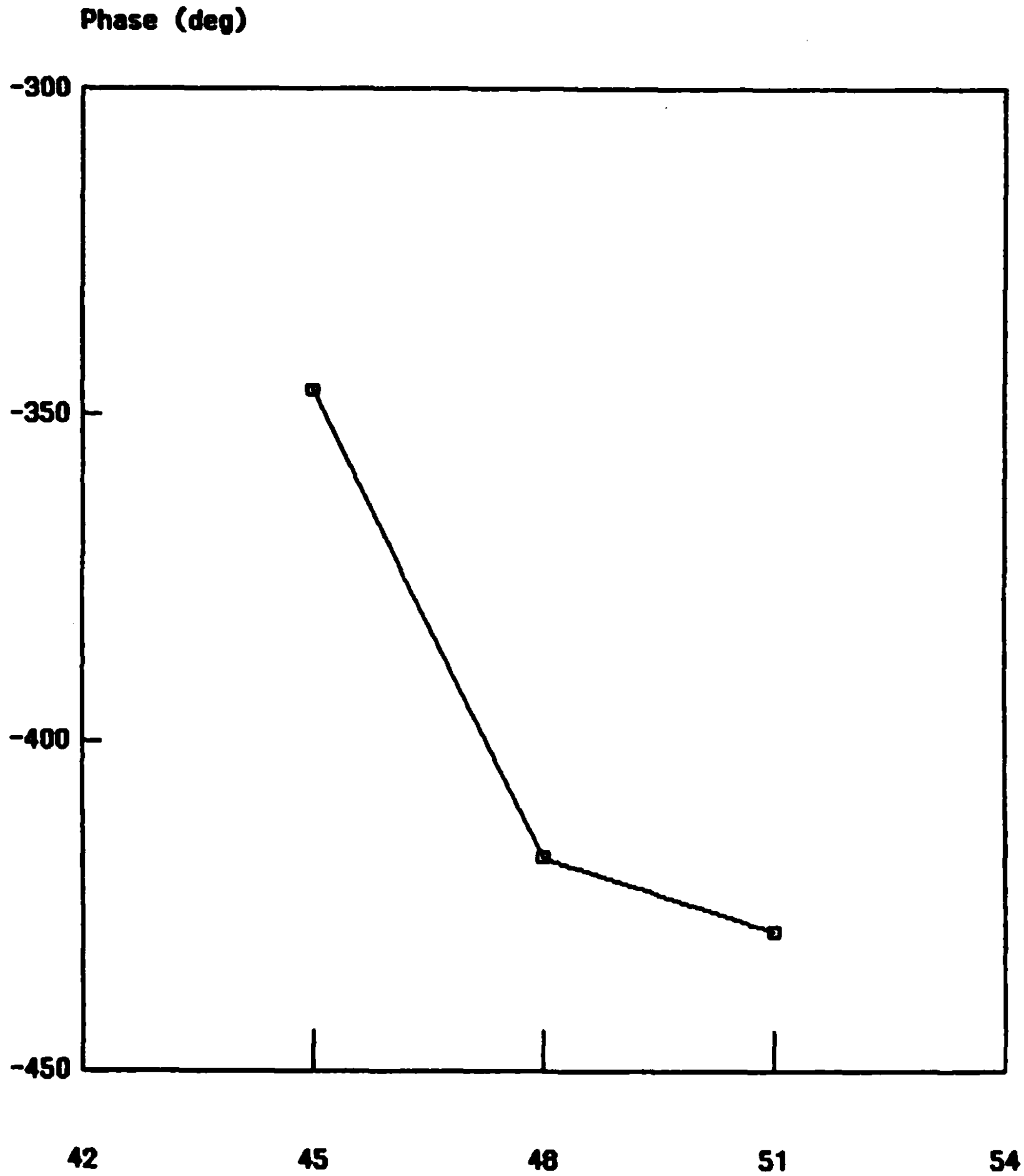


Figure 27. Phase by frequency of stimulation for each testing period (time of day in hours).

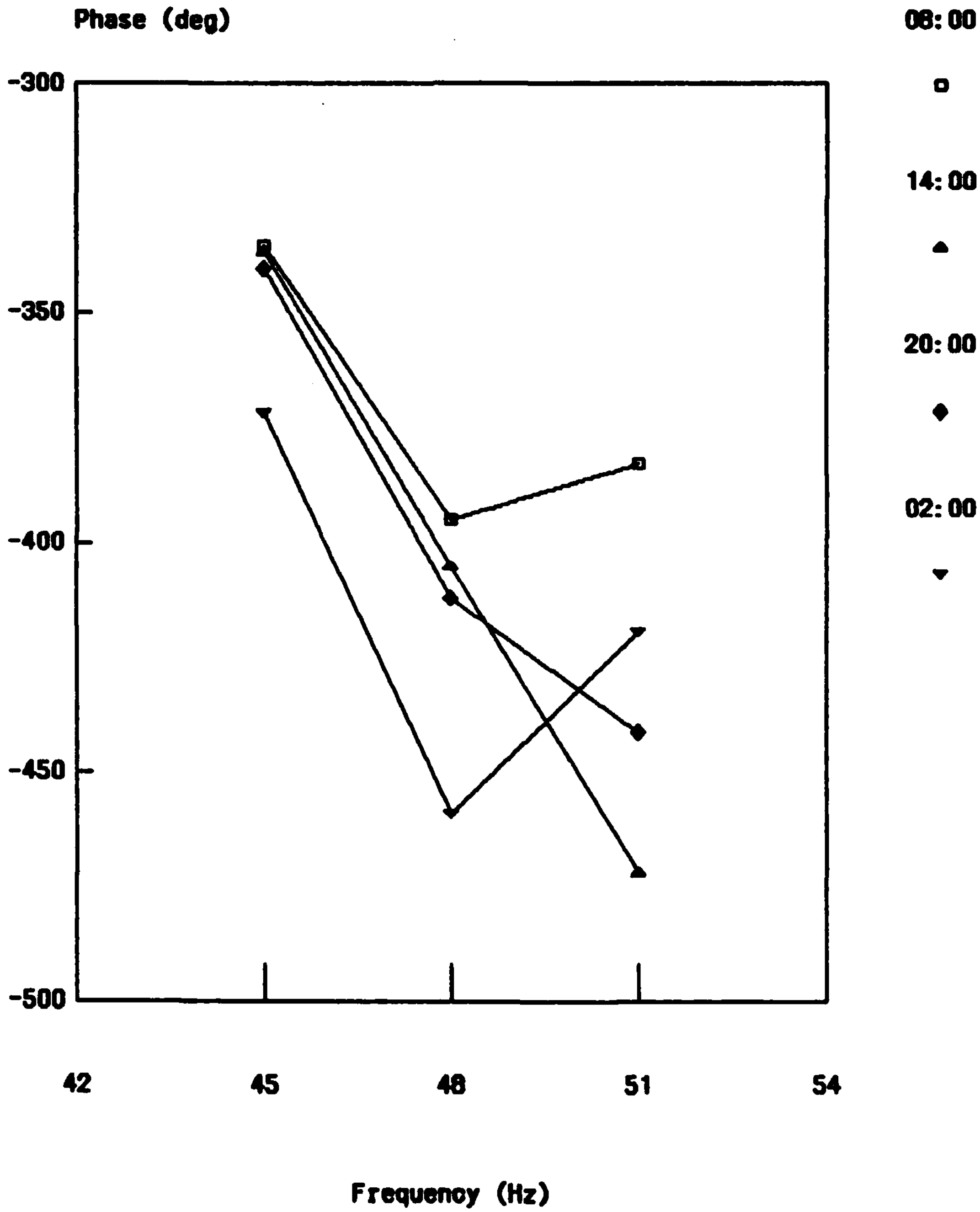
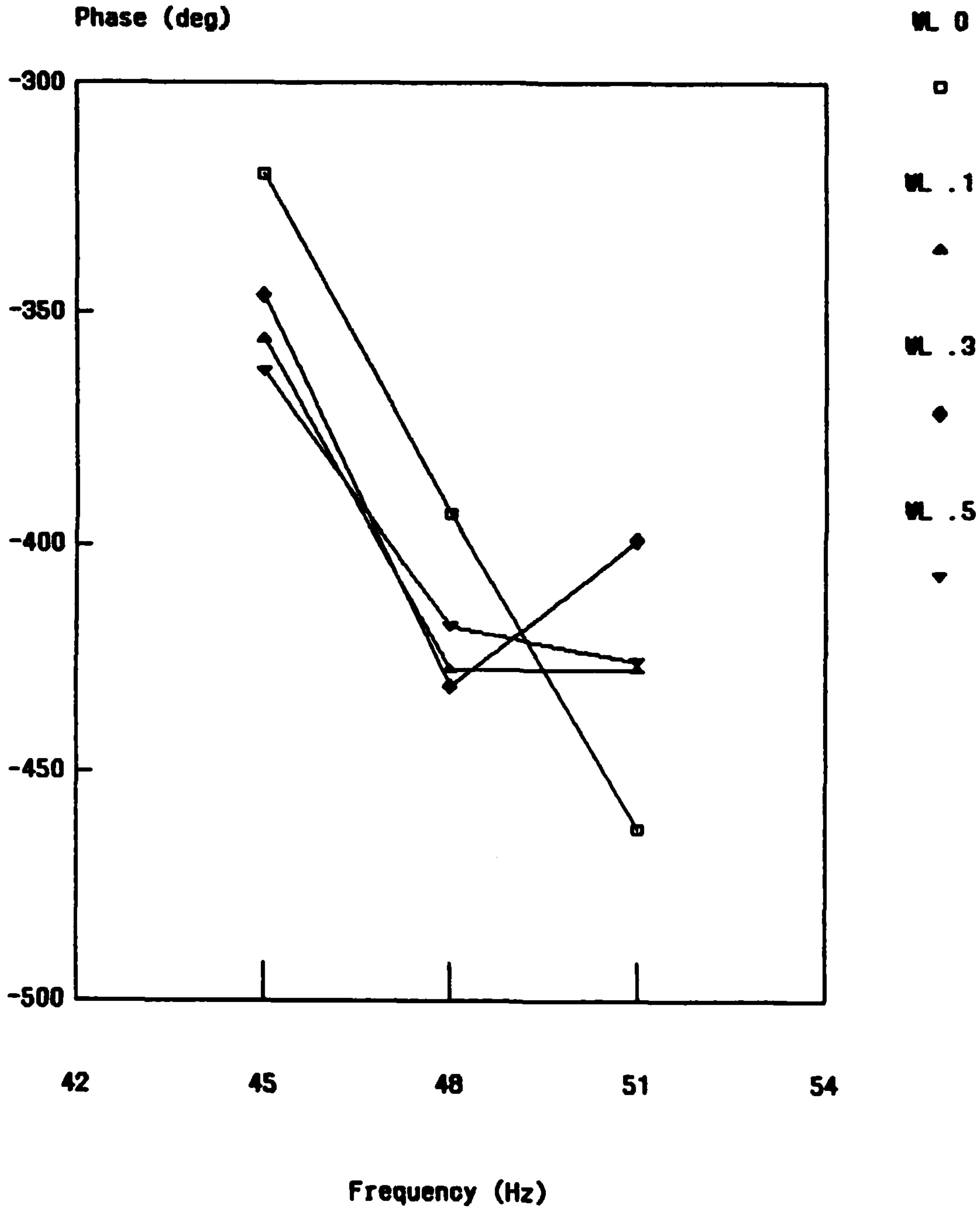


Figure 28. Phase by frequency of stimulation for each workload condition.



This is a disappointing result as our reading of the literature led us to expect that RTT would be an interesting measure of performance, if not color/brightness. However, it must be noted that several important differences exist in these studies and the one reported in 1981 by Wilson.

Wilson used memory and cognitive tasks in his studies while we used a tracking task. Clearly, the primary mental requirements for those tasks are different from our task. A well-practiced tracking task probably requires little in the way of memory or cognitive components as defined for Wilson's tasks.

In an earlier study, Wilson (1980) reported that phase lags for high frequency SSEPs were influenced by difficulty of a single-axis tracking task. Greater lags were generated when the task became more difficult. This matched our findings for phase lags at 45 Hz but not 48 or 51 Hz. The coherence measure decreased as workload increased until the most difficult level, when it increased (but not significantly). It appears that coherence and phase lag (at certain frequencies) may be useful indicators of workload.

Several important differences exist in our experiment and Wilson's 1980 report. We used a very different tracking task. Perhaps most important, Wilson selected the best frequency for each subject and examined the data from subjects separately. This would seem to be an excellent idea as we have seen clear individual differences in our own experiments. Since our purpose was to try and find generalizable techniques for potential application in operational settings, we did not fine-tune for each subject.

Although there were some SSEP correlates with fatigue (time of day), few of them were particularly useful in detecting differences that could not have been guessed by the use of paper and pencil fatigue rating scales. These studies suggest that SSEP measures are not particularly useful as fatigue measures and probably should not be pursued without careful attention to individual differences.

While RTT also did not show a correlation with color and brightness, it is clear that other SSEP measures are sensitive and can be successfully used across subjects. This seems particularly true of the coherence which produced significant correlations with color and brightness changes. Of particular interest is the identification of red transmitted light as less effective than other colors in producing robust SSEP driving.

Additional Research

The facility for steady-state Evoked Potential research which we have put together in the laboratories of the Psychophysiology Function at Brooks AFB is being used by other investigators for

their research. We have been able to share in some of these investigations and have been involved in SSEP studies of the Manikin and Perelli cognitive tasks. We had hoped to have preliminary data from these experiments available for presentation in this report, but the data had not been processed for presentation at the time of this writing. These data will be presented as a TR at Brooks as soon as possible.

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APPENDIX

Subjective Fatigue

The value of a check in each column is: Better Than = 2, Same As = 1, Worse Than = 0.

NAME AND GRADE			TIME/DATE
INSTRUCTIONS: Make one and only one (✓) for each of the ten items. Think carefully about how you feel RIGHT NOW.			
STATEMENT	BETTER THAN	SAME AS	WORSE THAN
1. VERY LIVELY			
2. EXTREMELY TIRED			
3. QUITE FRESH			
4. SLIGHTLY POOPED			
5. EXTREMELY PEPPY			
6. SOMEWHAT FRESH			
7. PETERED OUT			
8. VERY REFRESHED			
9. FAIRLY WELL POOPED			
10. READY TO DROP			

PREVIOUS EDITION WILL BE USED

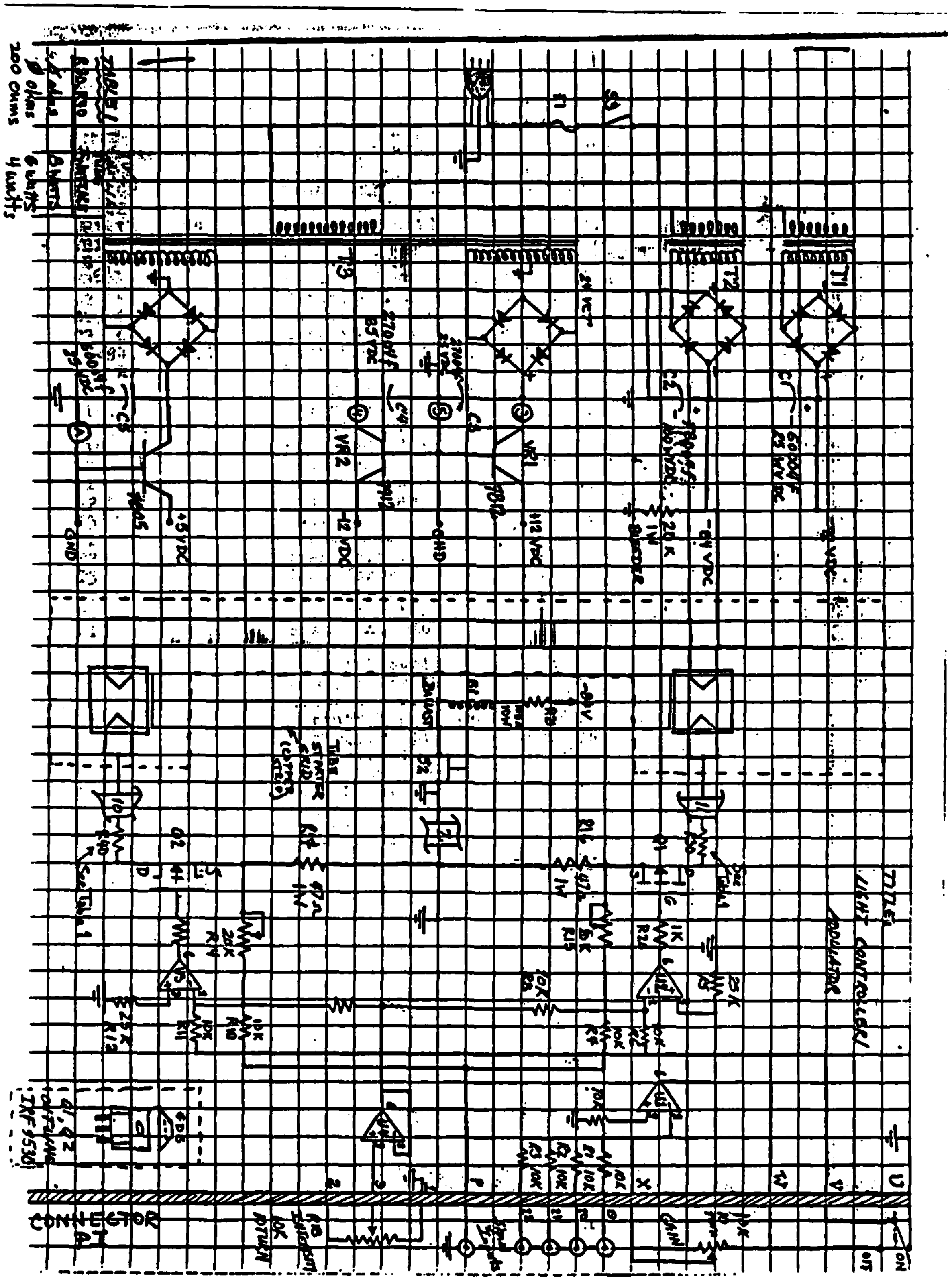
SAM FORM SEP 76 136 SUBJECTIVE FATIGUE CHECKCARD

Crew Status Check
(abridged)

NAME	DATE AND TIME
SUBJECTIVE FATIGUE *(Circle the number of the statement which describes how you feel RIGHT NOW.)*	
1	Fully Alert; Wide Awake; Extremely Peppy
2	Very Lively; Responsive, But Not At Peak
3	Okay; Somewhat Fresh
4	A Little Tired; Less Than Fresh
5	Moderately Tired; Let Down
6	Extremely Tired; Very Difficult to Concentrate
7	Completely Exhausted; Unable to Function Effectively; Ready to Drop
COMMENTS	

SAM FORM JUL 80 202 CREW STATUS CHECK

Schematic for Multiple Frequency Driving Circuit



Parts List for Multiple Frequency Driving Circuit

Qty	Schematic Reference	Description
3	Q1,Q2	Transistor, 1RF9530, (1 spare)
2	U1,U2	Dual Operational Amplifier, MC
4	CR1 thru CR4	Rectifier bridge, 100V, 2 Amp
1	VR1	Voltage Regulator, +12V, MC7812
1	VR3	Voltage Regulator, +5V, MC7805
1	VR2	Voltage Regulator, -12V, MC7912
4	C2	Capacitor, 2000uf, 100 VDC
2	C1,C5	Capacitor, 6000uf, 15 VDC
2	C3,C4	Capacitor, 3000uf, 50 VDC
10	R1-R4, R6-R11	Resistor, 10K, 1/4 watt
2	R5, R12	Resistor, 2.5K, 1/4 watt
2	R13, R20	Resistor, 1K, 1/4 watt
2	R16, R17	Resistor, 47 ohm, 2 watt
2	R18, R19	Resistor, 10 turn pot.Clarostat 73JA-10K
2	R14, R15	Resistor, 20K pot
1	R21	Resistor, 100 ohm, 10 watt
1	S1	Switch, power
1	S2	Switch, push-button, ALCO MPA 106F
1	S3	Switch, SPDT, ALCO MTA 106D
1	T1	Transformer, 6.3V, .6A
1	T2	Transformer, 60V CT, Triad F-279U
1	T3	Transformer, 24V CT, 9V CT,Triad F-166xP
1	B1	Ballast, 15 watt
1	F1	Fuse holder
1	F1	Fuse, 3A, 3AG
1		Power cord
1		Terminal strip
1		Lamp, power indicator
2		Knob, for 10 turn pot
1		Circuit board, Vector P/N
1		Connector, Circuit Board P/N
2		Flourescent Lamp, F8T5/cw
2		Ic socket
4		Lamp holders
1		BUD Mini Box B/N C1585 L G
12		Standoffs
2		Terminal strip
4		Tip Jack
1		Barrier Strip
4		BNC Connectors

Hardware, screws, nuts, wire, etc. as required.

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